STATIC ELECTRIFICATION

A symposium held by
The Institute of Physics in London
on 25, 26 and 27 March, 1953

BRITISH JOURNAL OF
APPLIED
PHYSICS

SUPPLEMENT NO. 2

LONDON
THE INSTITUTE OF PHYSICS
1953

Foreword

In the early part of 1951 a proposal was made to The Institute of Physics that a volume on the generation and effects of static electricity should be published in the Institute's series of *Physics in Industry* monographs. It was eventually decided by the Board of the Institute that, in the present state of knowledge of the subject, rather than to commission a monograph it would be preferable to hold first a conference covering all aspects of static electrification and to publish the conference proceedings as a supplement to one of the Institute's scientific journals. The conference was held at Bedford College, London, on 25–27 March, 1953, and the papers presented, together with an edited account of the discussion, are contained in this supplement. The papers were grouped into three main sections, namely general principles of the generation and dissipation of static electricity, useful applications of static electrification and harmful effects of static electrification. The first and third of these groups of specialized papers were introduced by general surveys of the fields concerned. In addition, Professor F. A. Vick opened the conference with a general lecture on contact electrification, and one session was devoted to papers on electrostatic machines, principally consisting of two papers dealing respectively with machines for the production of high energies and machines capable of supplying useful power. The arrangement of papers in this supplement follows the same pattern.

It was apparent in the early stages of the conference arrangements that the subject was one of great interest to a wide range of scientists and industrialists, chiefly because of the many processes and operations in which static electrification can be either a danger or a serious nuisance. The papers in this supplement probably comprise the most comprehensive account yet published of work in this field; at the same time they show the gaps in present knowledge and understanding of the process of electrification and of means by which it may be eliminated. It is hoped that this aspect may be no less valuable than the accounts of what has so far been achieved.

The Board wishes to record thanks to the members of the Organizing Committee who refereed the papers, to the authors for prompt and helpful co-operation in the revision of their manuscripts, to the editorial staff of the Institute and to the printers, Unwin Brothers Ltd., for their unfailing help.

N. Clarke
Conference Secretary

The Institute of Physics, London
November 1953

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Theory of contact electrification

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After an outline of the relevant parts of the modern theory of solids, the transfer of electrons when metals, semiconductors and insulators are placed in contact is discussed. The importance of surface states is stressed.

In the picture of static electrification usually attributed to Helmholtz[1] it is assumed that when two bodies are placed in contact there is a transfer of charge from one to the other to form an "electrical double layer" consisting of two layers of charge of opposite sign, one on or near each surface, and of the order of a few molecular diameters only apart. When the bodies are separated it follows that, provided each surface retains its charge, very large differences of potential can result from the reduction in capacitance, even if the original difference of potential between the two layers is quite small. The main effect of rubbing the two bodies together is supposed to be merely to increase the area of the double layer, the importance of friction being secondary by raising surface temperatures or by altering the nature of the surfaces themselves. Without such rubbing the transfer of charge will occur only at a relatively few places since, by molecular standards, the surfaces of most solids are rough. In some cases it is possible that a double layer may exist wholly on one body. Double layers may also be formed when a solid is in contact with a liquid and are of special importance in the generation of electrode potentials.

When two solids are in contact it is probable that in most cases the charges transferred are electrons, though in other cases movement of ions may be involved, directly or indirectly. If, as is generally believed, double layers are important in static electrification, it is desirable to know what factors determine whether electrons are transferred from one surface to another, in which direction they move and the magnitude of the resulting charge density. The difficulty of obtaining reproducible and predictable results in experiments involving electrostatic charging is notorious, and indicates that more than one mechanism may be involved, but any satisfactory theory must be based, at least in part, on a clear understanding of the process of electron transfer between solids of different kinds. During the last twenty years much work has been done, for quite other reasons, on the behaviour of electrons in solids but, with a few exceptions, very little of it has been applied directly to the problems of static electrification. The main purpose of this paper is to survey recent work which has a bearing on the formation of electrical double layers with particular reference to electron transfer, though some remarks are added concerning ions. The next section is intended to be a fairly elementary account of some electronic properties of solids for those not familiar with the subject.

Classification of solids

For the present purpose it is convenient to classify solids into electrical conductors (metals and alloys), insulators and semiconductors. A metallic conductor has a high conductivity which decreases with rise in temperature and which also normally decreases if impurities are added. An insulator has a very low conductivity (resistivity $\rho > 10^{11}\ \Omega$ cm). A semiconductor has intermediate values; the conductivity increases with temperature, and also normally increases with added impurity.

When considering the behaviour of electrons in metals, energy diagrams of the type shown in Fig. 1(*a*) are very useful. Energies *from the point of view of an electron* are measured upwards and distances horizontally. The potential of free space is represented by the level $V = 0$. An electron approaching a metal from free space is attracted into it, and work is required to remove an electron from a metal. The total

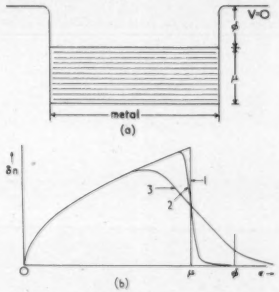

Fig. 1. Energy diagrams of metals

(*a*) Energy bands in a metal.
(*b*) Fermi–Dirac distribution of energies of electrons in a metal: (1) at absolute zero, (2) at about room temperature, (3) at a high temperature.

energy of a mobile electron within a metal is thus less than that of an electron at rest in free space. Electrons in metals are effectively in a "potential box." The bottom of the box is at a depth $(\phi + \mu) = W$ below $V = 0$. Energy differences ϕ and μ are usually measured in electron volts. It is a consequence of quantum mechanics, particularly of the exclusion principle, that even at the absolute zero of temperature only two electrons (of opposite spins) can occupy the lowest available energy at the bottom of the box. There is a whole range of "energy levels," very close together (i.e. with very small energy steps between them), which are derived from the energy levels of the valency electrons of the atoms which have combined together to form the solid. The total number of available levels is of the same order as the number of atoms in the lump of solid considered, and they form a band of energies of total height W eV. For metals this height is of the order of 4–15 eV (see the table below). At absolute zero the mobile electrons, which are the normal valency electrons of the atoms forming the solid and which can migrate from one atom to another when the latter are close-packed, as in a solid, occupy all the available energy levels from the bottom upwards. The highest energy possessed by an electron in a metal at absolute zero is that of the "Fermi level," μ eV above the bottom of the band. If the temperature is raised, then some electrons may acquire greater energies and occupy higher levels. Similarly if an electric field is applied, some electrons, near the Fermi level,

may gain energy from the field and rise to higher levels, and may also move through the metal in a general direction determined by the field. Such movement is possible only when there are vacant levels above the Fermi level.

The value of μ depends on the free electron density in the solid, as shown by the following expression:

$$\mu = \frac{h^2}{2m}\left(\frac{3n}{8\pi V}\right)^{2/3} \text{ ergs} \qquad (1)$$

where n is the number of electrons in a volume V, h Planck's constant and m the electronic mass. Some values of μ are included in the table.

Metal	$\mu(eV)$	$\phi(eV)$	$(\mu+\phi)$
Na	3·12	2·28	5·4
Cu	7·04	4·45	11·5
Au	5·54	4·9	10·4
Al		4·1	
Fe		4·5	
Mo		4·24	
Ni		4·96	
W		4·54	

The electrons are spread over the various available energies at a temperature $T°$ K according to the Fermi–Dirac distribution

$$\delta n = \frac{4\pi V(2m)^{3/2}}{h^3} \frac{\epsilon^{1/2}\delta\epsilon}{\exp\left[(\epsilon-\mu)/kT\right]+1} \qquad (2)$$

This is plotted in Fig. 1(*b*) for different temperatures, and it is clear that only those electrons having energies near the μ-level are affected by the temperature rise. At room temperature, the distribution is not very different from that at 0° K. The energy gap of the μ-level below $V = 0$ [Fig. 1(*a*)] represents the minimum energy required at $T = 0°$ K to cause an electron to escape from the metal into free space. The energy barrier, ϕ, is called "the work function," and some typical values are recorded in the table. The extra energy can be acquired in several ways: if by temperature, the number of electrons which escape is proportional to the area under the Fermi–Dirac curve to the right of energy $(\mu + \phi)$—see Fig. 1(*b*)—and is given by the thermionic emission equation

$$i = (1-r)(4\pi mek^2/h^3)T^2 \exp(-\phi/kT) \text{ e.s.u./cm}^2 \qquad (3)$$

where r a reflexion coefficient for electrons striking the metal surface from the inside. If e, the electronic charge, is measured in coulombs, $4\pi mek^2/h^3 = 120$. The work function, ϕ, is slightly temperature dependent, but this is not important here. For photoelectric emission the minimum frequency of light which is effective is ν_0 where $\phi = h\nu_0$.

For insulators, such as pure ionic, valence and molecular crystals, the situation is different. The valence electrons are normally bound to the ions or atoms forming the lattice, and there are no vacant energy levels immediately available to them which will enable them to move through the solid as a whole. The relevant energy bands are indicated in Fig. 2.

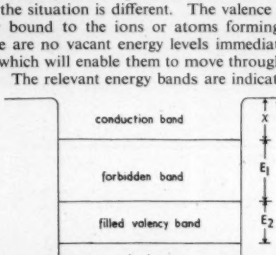

Fig. 2. Energy bands for an insulator

Above the band giving the range of energies of the valence electrons, which contains no free or empty levels, there is a "forbidden band" of energies. This arises because for these energies the wavelengths associated with the electrons are such that the electrons would be reflected from the atomic planes in the crystal, just as X-rays are, according to the Bragg relation. For details, the reader should consult the treatment of Brillouin Zones given in some of the general references listed below in the Bibliography [such as (*e*, *g*)]. Above the forbidden band, there is a conduction band of allowed energies, forming a potential energy box of depth X electron volts. The value of X is of the order of 1–5 eV, and of E_2 for most non-metallic solids 5–10 eV. In some cases, however, such as silicon and germanium, E_2 is of the order of 1 eV or less and even at room temperature an appreciable number of electrons are able to acquire enough energy to rise from the full band to the conduction band, and the solid is then called "an intrinsic semiconductor." The number of electrons in the conduction band is given approximately by[2]

$$n = \left[2(2\pi mkT)^{3/2}/h^3\right] \exp(-E_1/2kT) \qquad (4)$$

$$n = 5 \times 10^{15} T^{3/2} \exp(-E_1/2kT) \qquad (4a)$$

so that for most insulators the number of electrons in the top band and the conductivity are both negligible. In principle, such insulators would become conducting at very high temperatures, but in practice many solids melt first.

The energy bands of semiconductors are similar to those of insulators but with the addition of isolated levels within the forbidden zone at specific points in the solid, as shown in Fig. 3. There are two main types of semiconductor, in

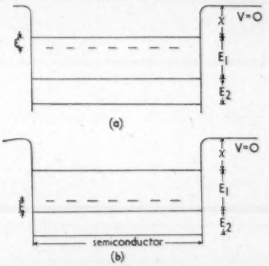

Fig. 3. Energy bands of semiconductors
(*a*) Excess or *n*-type.
(*b*) Defect or *p*-type.

addition to the intrinsic mentioned above. In the excess or *n*-type the extra levels are not far below the conduction band and normally have electrons in them. In the defect or *p*-type the extra levels are just above the full band and are normally empty. In the first case the levels are sometimes called "donor" levels and in the second, "acceptor" levels. The conductivity of a semi-conductor is given by $\sigma = neu$, where n is the number of charge carriers per unit volume, and u the "mobility" of the charges, i.e. the drift velocity in unit applied field. In many cases the variation of mobility with temperature is small compared with the variation in n (though not always), which is given by[2]

$$n = 2n_0^{1/2}\left[(2\pi mkT)^{3/4}/h^{3/2}\right] \exp(-E/2kT) \qquad (5)$$

where n_0 is the number of donor or acceptor levels per unit volume. This expression does not apply, of course, if the

temperature is sufficiently high for all electrons to have left the donor levels and entered the conduction band, when the variation of σ with T becomes more like that of a metal. In an *n*-type semiconductor the carriers of charge are electrons, but in the *p*-type they are the "holes" left in the full band after electrons have gone from it to acceptor levels. These holes move under the influence of an applied field as though they have positive charges, and this gives rise to what used to be known as the anomalous Hall Effect (for example).

The additional levels in semiconductors are usually due to defects of some kind in the lattice of the solid. In ionic crystals they may be due to atoms in interstitial positions, either additional atoms introduced from outside the crystal, or atoms which have migrated from their lattice positions. A lattice position from which a negative ion has moved forms an "electron trap," i.e. a centre of attraction for an electron. Such trapped electrons alter the optical absorption properties of the crystal and are called "F-centres." If there are an appreciable number present, the crystal may become coloured. A very small proportion of impurities or defects—less than one part in a million—is sufficient to produce marked semiconducting properties. Equation (5) holds only when this proportion is small. At higher values of n_0, E is no longer independent of n_0. By heating in oxygen or hydrogen the electron states of cations or anions in some oxides may alter, and thus give rise to extra levels. By substitution of some atoms in the lattice by others of higher valency—e.g. germanium by phosphorus—an effective excess positive charge is created in each place which can hold an electron, thus forming an extra level. Controlled valency semiconductors are now an important group.[3]

In addition, extra levels may be created by defects of various kinds at the surfaces of crystals, and these may be specially important in multicrystalline solids. They are discussed below with reference to their effects on electrical double layers.

For further information on semiconductors, items (*d*, *e*, *f*, *g*, *h*, *j*) in the bibliography should be consulted.

CONTACT BETWEEN TWO METALS

In Fig. 4(*a*) the important energy levels in two separate pieces of different metals are shown. When these pieces are caused to approach each other, as soon as they are close enough for the wave-mechanical tunnel effect to become operative, electrons will flow from the metal with the smallest value of ϕ (i.e. from the one with the highest μ-level relative to $V = 0$) until the μ-levels in the two metals are the same. This last statement is strictly true only at $T = 0°$ K, and at higher temperatures the electrons will flow until the number

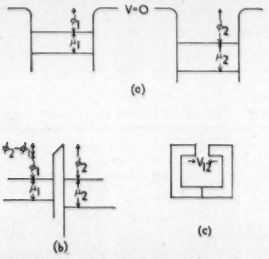

Fig. 4. The contact between two metals

in each available level is statistically the same in one metal as in the other, but, as we have seen, the conditions at room temperature are not very different from those at absolute zero. Electrons flowing from the metal with the smallest value of ϕ leave behind an equivalent positive charge. These charges remain, in general, near the boundary between the two metals, forming an electrical double layer. There is across the boundary a potential step $= \phi_2 - \phi_1$, as shown in Fig. 4(*b*). If the other ends of the two metals are separated, as in Fig. 4(*c*), there will be an equivalent difference of potential between the two faces, and this can be measured in various ways as the "contact potential difference" V_{12}.[4,5] It will be seen that

$$eV_{12} = \phi_2 - \phi_1 \tag{6}$$

If the separated surfaces of Fig. 4(*c*) are brought into contact the potential steps at the two junctions will be equal and opposite unless one junction is at a different temperature from the other, when the equilibrium will be upset and a thermal e.m.f. generated. Contact potential difference, being the difference between two work functions, is of the order of 0·1–3 V for metals. It has long been known that the value of ϕ for a metal depends very largely on the state of the surface. For example, a monomolecular layer of oxygen on tungsten changes the work function from 4·54 to about 6·3 eV, and a monomolecular layer of barium to 1·6 eV. The contact potential difference is just as sensitive to surface conditions as the work function ϕ. Even for the same clean metal, ϕ may change slightly according to the crystal plane exposed.[6] Fig. 5 shows in very diagrammatic form the

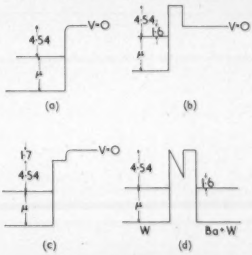

Fig. 5. Potential barriers

(*a*) W; (*b*) W + Ba; (*c*) W + O; (*d*) the contact between W and Ba + W.

potential steps near the surface of (*a*) pure tungsten, (*b*) tungsten with a monomolecular layer of barium, (*c*) tungsten with a monomolecular layer of oxygen. In surface (*b*), electrons can penetrate the thin barrier above the level $V = 0$ by wave-mechanical tunnel effect. Fig. 5(*d*) shows what happens when surfaces (*a*) and (*b*) come close together.

It may at first appear that the double layers formed by the contact of two metals (or two pieces of the same metal with different surface contaminations) are not important in static electrification because all the charges (being mobile in the metals) might be lost at the last stages of separation. It has long been known, however, that metal powders blown against metal surfaces can acquire charges and high potentials.[7,8] Harper[9] has recently demonstrated directly that at least one cause of electrification of metal surfaces when brought into contact with one another and separated is due to the contact potential difference between them. Recognizing that, as

mentioned above, rubbing between the two surfaces may bring other mechanisms of charging into play, Dr. Harper devised two methods of eliminating, as far as possible, all sliding of the two metal surfaces as they were brought together or separated. Polished metal spheres were used and they were cleaned carefully, but no attempt was made to degas them in a high vacuum. It is likely, therefore, that the surfaces were covered with thin films of oxygen or oxides. In most cases the spheres were steel ball bearings electroplated with the metal under test. These surfaces were reasonably stable over periods of hours. In one method, the ball was floated on mercury and could be moved up and down a vertical cylinder. The second made use of a lever mechanism to move the ball. It was shown that for a particular pair of spheres with given surfaces, the amount of charge separated was always the same. Now contact potential differences between (e.g.) surfaces A and B, and B and C are additive, so that if the separation charges are due to these potential differences, they should be additive too. Harper found this to be so. He was able to calculate approximately the amount of charge transferred in terms of the contact potential difference and this was found to agree with experiment, provided that the effective contact potential difference was measured for the actual surfaces used.

We may take it, therefore, that on both theoretical and experimental grounds one cause of static electrification of two metal surfaces which have been brought into contact is the contact potential difference, which, in turn, depends upon the difference between the work functions of the two surfaces. For the charges to remain, the pieces of metal must be on insulating supports, of course.

THE CONTACT BETWEEN A METAL AND A NON-METAL

For a perfect insulator in contact with a clean metal, the energy levels will probably be as in Fig. 6. For those insulators for which approximate values are available, χ is normally less than 1 eV whereas ϕ, for metals important in this context, is of the order of 4 eV. It is unlikely, therefore, that electrons

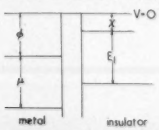

Fig. 6. The contact between a metal and an insulator

will be able to flow from metal to insulator, and there will be no electrons in the conduction band of the insulator to flow to the metal. If ϕ were to be reduced by, for example, an electropositive adsorbed layer, the reduction of $\phi - \chi$ might be sufficient to allow some thermionic emission from metal to insulator even at moderate temperatures, but it is more likely that the metal will be covered by an electronegative layer, such as oxygen, which would raise ϕ. Other possible mechanisms for transfer of electrons would be photoelectric emission and field emission.

In practice, the insulator may be by no means perfect. If it contains sufficient impurities, it may become a semiconductor and fall within the province of the next section. While remaining an insulator, however, there may be additional levels on the surface of the insulator which can act as acceptors or donors of electrons (see below). In these cases there may easily be a transfer of electrons between the metal and the surface levels on the insulator, the magnitude and direction of the flow depending on the nature, energies and concentration of the surface levels with respect to the μ-level of the metal. These factors may depend on the previous history of the insulator and the resulting charge transfer is difficult to predict with our present knowledge.

THE CONTACT BETWEEN A METAL AND A SEMICONDUCTOR

It will be convenient to base the discussion in this section on the behaviour of an n-type semiconductor in contact with a metal. A p-type semiconductor will differ in detail but not in fundamental principles. Just before the approach of a metal to an excess semiconductor becomes close enough for the wave-mechanical tunnel effect to become operative, the energy levels will be approximately as in Fig. 7(*a*). As soon as electrons are able to flow, some will leave the conduction band of the semiconductor to fall down the potential step

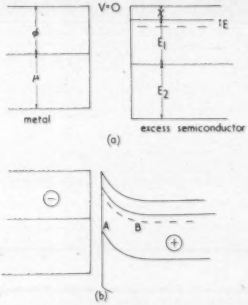

Fig. 7. The contact between a metal and an excess semiconductor

into the metal. This will continue until the potential distribution in the semiconductor is such that beyond the point B [Fig. 7(*b*)] the bottom of the conduction band of the semiconductor is about $\frac{1}{2}E$ eV above the μ-level of the metal, at room temperature. This case was first considered by Mott[10,11] and forms the basis of his theory of barrier-layer rectification. The region AB in the semiconductor forms a potential barrier to the flow of further electrons to the metal in the absence of applied field in the right direction. The height of the potential barrier is nearly $\phi - \chi$. At equilibrium, there is a net positive charge on the semiconductor and a negative one on the metal, forming an electrical double layer. On subsequent separation, most of the charges may be retained by semiconductors and metal (if insulated from earth), but there will be some redistribution since electrons can flow in each solid, and the final surface potentials may no be high.

THE EFFECT OF SURFACE STATES

According to the theory just outlined, the higher the value of ϕ for a metal in contact with a semiconductor, the higher the resulting barrier $\phi - \chi$. The accepted theories of rectification, due to Mott and to Schottky, predict that the degree of rectification of such a contact depends directly on the barrier height and therefore on ϕ. Some experiments, however, have given very poor correlation between ϕ and the degree of rectification. These results, and others, have led in recent years to a re-examination of the energy levels concerned.

Twenty years ago, Tamm[12] postulated the existence at the surfaces of perfect insulators additional levels within the forbidden zone of energies which are capable of trapping electrons. According to Shockley[13] the number of such surface "states" is equal to the number of surface atoms, and in a neutral crystal they are half-filled. Surface states may also result from lattice imperfections at the surface, adsorbed atoms, etc. In an important paper, Bardeen[14] has investigated the effects of a relatively high density of surface states, giving rise to a double-layer on the free surface of a semiconductor or insulator. He shows that if the density of surface states is about 10^{13} per cm^2 or more, the energy distribution near the surface will be rather like the right-hand side of Fig. 7(*b*), even without the adjacent metal. Electrons in the semiconductor conduction band fall into the surface levels and are trapped there. The rectification properties of such a semiconductor in contact with a metal will be almost independent of the work function of the metal.

It is evident that such surface charges may modify considerably the transfer of electrons when solids are placed in contact, and that, for example, the contact potential difference will not be just the difference in work functions. In a semiconductor, the surface levels will be filled by electrons from the conduction band. The negative charge itself will be of atomic thickness, but the positive charge may extend to perhaps 10^{-4} cm below the surface. The semiconductor as a whole will be neutral and the height of the potential charge at the surface of the order of an electron volt or less.

For an insulator, the surface states cannot attract many electrons from the solid, since they are not mobile, but may remain unfilled until electrons can be acquired from outside, e.g. by contact with another solid. The resulting surface charge is then not balanced by a positive space charge below the surface when the second solid is removed. Since the density of surface states may approach that of surface atoms, say 10^{15} per cm^2, if all these are filled with electrons, the surface charge density would be about 5×10^5 e.s.u./cm^2, which is greater than the highest observed as a result of electrostatic charging.[15] At these densities the surface field would be such that a brush discharge would result. Looking again at Fig. 6 and adding at the surface of the insulator a large number of levels over the whole range E_1 we see that even at very low temperatures the surface states with energies within the range $(E_1 + \chi - \phi)$ will be filled by transfer from the metal and the charge density will be quite sufficient to account for those observed when a metal and insulator are brought into contact and then separated. Similar considerations apply to the contact between insulator and semiconductor.

When one remembers that surface states may be due, in part, to imperfections in surface structure and to adsorbed atoms, and that these may depend upon the immediate past history of the particular surface considered, the complexity of the problem in practice is apparent.

DISCUSSION

In the preceding paragraphs we have discussed what is effectively the Helmholtz theory of static electrification in the light of the modern theories of solids. It is possible in principle to predict the magnitude and direction of the flow of electrons between two such solids in contact. In many cases in practice, however, the presence of surface states complicates the picture. The states, acting as traps for electrons, may originate in various ways, including imperfections of the lattice structure at the surface, the presence of adsorbed atoms, etc., and the precise condition of the surface may depend on its immediate past history. The surface density of charge due to such states may be high enough to cause a brush discharge from the surface when the two solids originally in contact are separated, and the bombardment of the surfaces by the resulting high speed electrons and ions may again alter the surface structure. The density of surface states on an insulator may vary from place to place on the surface. In addition to electron transfer, there may be movement of ions, especially when the local surface temperatures are high or contact with liquid is involved.

In conclusion, I would plead that the planning and interpretation of experiments are carried out in the light of such knowledge of the structure and electronic properties of the various solids as we possess. Carefully controlled experiments may give important additional information about solids. More contact is needed between those interested in static electrification and those working on the fundamental properties of non-metallic solids, so that ideas and information may flow both ways.

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Survey of generation and dissipation of static electricity

By P. S. H. Henry, Ph.D., F.Inst.P., The British Cotton Industry Research Association, Manchester

A general account is given of the principles used in measuring contact electrification, and of the difficulties due to discharges in air and to unknown contact areas. The nature is discussed of the information which we might hope to obtain from work on this subject, and a list is made of the various mechanisms which have been proposed in the past, together with one new hypothesis. The suggestion is made that these are by no means mutually exclusive, and a simple form of theory is worked out to illustrate how several of them might be expected to operate together.

The electrification of insulating bodies by contact or friction is an old subject, but one which has received little attention since the early days of its discovery until lately, when its growing, and largely unwelcome, prominence in industry and commerce has forced us to take note of it. Perhaps this neglect has been because of its reputation for unrepeatability; but whatever the cause, few workers have published more than one or two papers on the subject. The literature is thus sporadic, with little to show in the way of evolution of the subject. Indeed, it would scarcely be an exaggeration to say that the state of our knowledge of it was little more advanced in 1940 than it was 50 years ago. Under these circumstances a general survey of the literature would be difficult to carry out with any compactness, and no attempt is made to do this below. Instead, it is intended to give in very elementary terms a background to the papers that follow, using only such references to the literature as may serve the purpose. To this is added some frankly speculative matter, the only excuse for whose introduction into a general survey is that it is designed to throw existing ideas into perspective with each other, rather than to introduce any new theory. A few comments are made on some practices which have led to confused thinking in the past.

In its broadest terms, the phenomenon in which we are interested is simply this, that if two surfaces are brought together and separated, either with or without obvious rubbing, charged particles are found to have crossed the boundary, with the usual result that the two surfaces have gained equal opposite charges. It would perhaps be surprising if the fields of force were so balanced that no transfer of particles took place, and from this point of view our task is not so much to seek for a reason why the transfer happens, as to find out how many of the various circumstances are relevant, and to what extent. We also have to account for the presence of mobile charged particles on one or both of the surfaces if these are insulators. A simple calculation shows, however, that we do not have to explain a massive migration of ions across the boundary: if we take the highest surface charge density which the author has seen reported as the result of contact—500 e.s.u./cm^2 (see the contribution by J. A. Medley in this supplement[1])—we find that it represents one electronic charge in 10^4 Å^2. If we assume, say, 10 Å^2 to represent an arbitrary "molecular surface area," we see that production of the charge density mentioned requires only that one ion should move across for every 1000 "molecular surface areas." To explain charge densities of the magnitudes normally observed after separation of two surfaces in air we do not need more than one ion to move across for every 10^5 "molecular surface areas."

Let us now consider the quantities that have to be measured.

MEASUREMENT OF CHARGE

The fundamental measurement which we would like to make is usually that of charge per unit area of contact under specified circumstances.

Here the author wishes to protest against the practice (which is very common, particularly in the technical press as distinct from the academic), of referring to the potential of an insulator. This habit arises from the predominance of current electricity, where one is dealing with conductors whose potential, in the absence of current, is the same all over, and is often maintained constant by connexion to a battery or generator. In dealing with static electricity we cannot speak of the potential of an insulator, for it will vary from point to point, and will also change as neighbouring bodies are moved about. What does remain constant, in the absence of a current, is the charge on a body, which is a definite quantity and does not vary as the relative positions of objects and other charges is altered.

The charge is usually measured, if an absolute value is wanted, by the method of the Faraday cylinder, in which the charged body is almost, or completely, enclosed by a conductor, preferably placed inside an earthed screen. A charge equal to that on the body is conducted to, or induced on, the outside surface of the "cylinder," and if we measure with an electrometer the potential to which it rises, we only need to know the capacity to earth of the system cylinder-electrometer to determine the charge on the body. The capacity can be measured by a variety of methods, for instance that of sharing a charge with a standard condenser.

A refinement available where a valve electrometer provided with a "guard ring" terminal (e.g. the Baldwin–Farmer[2] electrometer) is being used is to connect the screen round the Faraday cylinder to this terminal instead of to earth. By this means not only is the leakage to earth reduced by a factor which may be as high as 100, but the effective capacity to earth is reduced by the same factor, leading to high charge sensitivity.

It is not always possible to have the experimental body even approximately surrounded by a conductor, and then use is usually made of a "probe" electrode, consisting of a conductor exposed to the field from the charge to be measured, and connected to the electrometer. The potential to which the electrode comes as the result of a point charge in its neighbourhood will be proportional to the charge, but since the induced charge on the electrode is no longer equal to the inducing charge the necessary "induction coefficient" for deriving the point charge from the observed potential is no longer equal to the capacity to earth of the detecting system, and is more difficult to determine. Since experimental bodies cannot usually be regarded as point charges, the induction

coefficient will vary with the distribution of charge on the body, even if the size and shape of the latter remain constant. Consequently the method is not readily adapted for making absolute measurements, but is very useful for relative measurements when the position, size and shape of the sample can be kept constant. Several authors have attempted to calibrate apparatus of this type by introducing a conductor of the same shape as the insulating samples to be used, raising it to various known potentials, and plotting electrometer readings against these potentials. The results of measurements on insulating samples are then quoted as the "potential of the sample" by using this curve. Apart from the inadvisability of speaking of a quantity whose order of magnitude, even, depends upon the position of surrounding screens, etc., as if it were a property of the sample, it should be realized that this method does not in practice give the potential at any point of the sample. The distribution of charge on the conducting sample will usually be quite different from that on the insulating sample, owing to the proximity of the probe electrode and its screen. Figures quoted thus are usually best regarded as giving in arbitrary units values for the charge density on the sample. In the author's opinion it would be better to give the figures in frankly arbitrary units, such as electrometer readings. Probe electrodes *can* be calibrated in absolute terms if, for instance, an *insulating* sample can be used of the same shape, position, and charge distribution as those to be measured, but capable of being removed and dropped into a Faraday cylinder. Alternatively, the induction coefficient can sometimes be calculated, as when the sample is flat and the probe electrode is a flat plate parallel to the sample and at a distance from it small compared with its dimensions, and all other bodies are at a much larger distance. The induced charge can then be assumed approximately equal to the charge on an area of the sample the same as that of the electrode, and the case is similar to that of the Faraday cylinder although the electrode does not surround the sample.

Portable instruments made up in the form of a pistol, and comprising a probe electrode and valve electrometer, all screened except for a small aperture, have been made which are extremely useful for relative measurements *in situ* in the factory.[3,4]

EFFECT OF DISCHARGE IN AIR

It is comparatively easy to measure the charge on a body after it has been separated from another surface in air. A serious limitation to the utility of such experiments lies in the fact that the charge measured thus may be much less than that which existed on the body during the early stages of separation. If we take the breakdown strength of air at atmospheric pressure to be 30 000 V/cm, we find that the maximum free charge density on a smooth flat surface in air is about 8 e.s.u./cm^2, or 16 e.s.u./cm^2 for a flat sheet, counting both sides. Several experimenters[5,6,7] have, in fact, found that charge densities, measured in air, on surfaces which have just been separated after good contact with other surfaces frequently come up to this limit, suggesting that the density was originally higher. This supposition has recently been verified for a particular case by Medley.[1]

No way over this difficulty which does not impose considerable restrictions on the experimenter is known to the author. Possible methods are:

1. Working in a vacuum. Several experimenters[1, 8, 9] have used this method, either to reduce electric discharge or to avoid contamination of a clean surface. For the latter purpose it is, no doubt, essential, but by the same token it prevents investigation of the effect of moisture absorption, and the use of surfaces as they occur under normal circumstances. Also it makes the experiment difficult.

2. Working in air under pressure. The author has not seen this method applied, but since the potential gradient which air in bulk can support is proportional to the density, each extra atmosphere adds another 8 e.s.u./cm^2 to the surface charge which can exist. The experimental difficulties would be at least as great as with the vacuum method, but the necessity for dryness no longer exists.

3. Restricting the air to a thin layer. The field strength which can be supported by air increases greatly when the gap becomes too narrow for effective multiplication of ions by collision. At atmospheric pressure, the gap would have to be only a few microns wide in order to make use of this effect but, by Paschen's law, corresponding conditions occur if the gap varies inversely as the pressure, and at a few millimetres of mercury pressure a gap of 1/10 mm would enable considerably increased fields to be supported without breakdown.[10] It is possible that an accurate sliding or rotating motion would enable this effect to be utilized when it was not desired to use a high vacuum, but the most useful application is in connexion with the next method.

4. Use of samples in thin sheet form backed by conductors. This is the method described by Medley.[1] He uses the induced charge on an earthed conductor behind the sample to cancel out most of the field due to the charge to be measured—the principle of the bottom plate of the electrophorus. This protective effect does not come into action until the distance between the retreating surfaces is comparable with the thickness of insulating sample. Medley used it in a high vacuum, but with samples a few hundredths of a mm in thickness it could be used, as suggested in the last paragraph, at a pressure low compared with atmospheric but sufficient for samples to be used under normal conditions of moisture content.

CONTACT AREA

The true area of contact is difficult, if not impossible, to determine. Perhaps the best one can hope for at present is to make it bear a reproducible ratio, for a given specimen, to the apparent area, and to content oneself with stating the latter. Methods which have been used are as follows; it will be noticed that all except one severely restrict the choice of one of the two surfaces.

1. The use for one surface of a liquid which does not wet the other surface; e.g. mercury against non-metallic surfaces,[1] or water against non-polar surfaces.[11] The true area of contact, supposing it to be definable, is probably less than the apparent area.

2. The use for one surface of a liquid which wets the other surface and then solidifies, e.g. by evaporation of a solvent.[5,6] The resulting solid film is then peeled from the other surface. It may be supposed that the true area of contact in this case would be greater than the apparent area owing to irregularities in the surfaces.

3. The use for one surface of a transparent substance through which the interface can be examined when the two materials are brought into contact. Areas of "contact" are then shown up by extinction of total reflexion at the interface.[12] This method has been used in other connexions, but might not be reliable for our purposes, since total reflexion will be extinguished if the surfaces approach within a distance which, though smaller than the wavelength of the light, may still be large compared with the distance (25 Å) over which, according to Harper,[13] electrons can just cross the gap with appreciable frequency.

4. The use of a measured total force between the surfaces. The work of Bowden and others[14] has suggested that when two surfaces come together with sufficient force to produce plastic flow of one of them at the points of contact, the value of the local pressure remains surprisingly constant for a given pair of materials at the "yield pressure" of the softer material. As long as this is so, the true area of contact can be calculated by dividing the total normal force by the "yield pressure" of the softer material. The force can easily be measured, and the yield pressure determined by methods described in the reference given above. This way of finding the contact area should be of more general applicability than the other three.

THEORY, INCLUDING INTERPRETATION OF EXPERIMENT

Much of the information that we would like to have about static electrification can be summed up in the following five questions, of which the last is by far the most comprehensive.

1. What are the charged particles which cross the boundary?
2. How do they get there, and when?
3. How many are present?
4. Up to what distances can they cross the gap?
5. What conditions decide how many cross which way?

We will briefly comment on the first four, and devote a little more consideration to number 5.

1. There is little direct evidence on this point. Probably the only writer who has been quite explicit is Harper,[13] in discussing his experiments with metal-metal pairs, where there can be little doubt that the particles concerned are electrons. This may well be true also of other cases, but several writers[17,18] have reported an effect of the acidic or basic nature of a surface on the sign of charge it acquires by contact, which suggests the transfer of atomic ions. This suggestion is particularly cogent in the work of Shaw and Jex[9] on the effect of treating a glass surface alternately with acid and alkali. A minute remnant of acid on the surface caused it to go negative with respect to certain metals, whilst alkali on the same surface made it positive, the simplest explanation of which is to suppose that H^+ or OH^- ions can cross over. The "tunnelling" ability of electrons should make their transfer easier in the face of a given potential barrier than that of atomic ions, and it is interesting to speculate whether electrons may not usually "have the last word" in controlling contact electrification by reason of their ability to cross the gap later than other particles as the surfaces separate. In view of the known connexion between oxidation-reduction processes and electron affinity, it would be interesting to know more about the effect on static electrification of the state of oxidation of a surface.

2. We have to consider not only why the charged particles are there, but whether they were there before contact took place, or whether they were produced by the contact or friction (if any).

If they were there before, they may be

(*a*) electrons in a conductor or semi-conductor; or
(*b*) ions on the surface as contamination (not many are needed to explain observed charge densities, as mentioned above); or
(*c*) ions originating from fixed ionizable groups, forming part of the substrate, which ionize when there is a polar body (e.g. a water molecule) near at hand to reduce the energy required.

If the charged particles are only produced when contact or friction take place, they may be formed

(*a*) by thermal decomposition of organic substances following heat production by rubbing; or
(*b*) by ionization of fixed ionizable groups, the other surface providing the counter attraction which enables the ion to leave its parent body.

3. The total number of mobile charged particles on the surface is, of course, quite a different matter from the number that cross the boundary and produce net charges on the surfaces. A neutral surface may have equal numbers of mobile ions of both signs on it, or alternatively the ions of one sign may be fixed; that is to say, there may be ionizable groups attached to the surface, which may or may not be ionized before contact with the other surface.

4. The question of the longest distance over which the charged particles can pass from one surface to the other with sufficient frequency to affect observed charge separations has been discussed for the case of electrons by Harper,[13] who took 25 Å as the limit. Any charged particle would necessarily have to surmount (or "tunnel" through) a considerable potential barrier in passing from one surface to another when the distance is greater than atomic dimensions, if only because the "image forces" would tend to prevent its leaving the parent surface. At ordinary temperatures, with kT much smaller than the energy required to take an ion over the barrier, a sufficiently frequent passage across the gap could only be achieved by the tunnelling process, and would therefore be restricted to electrons. The last distance for passage of atomic ions as the surfaces retreat would presumably be much smaller than 25 Å, perhaps a few ångströms. This would not necessarily hold true at higher temperatures approaching those at which thermionic emission takes place.

5. The problem of finding out how the nature and conditions of the surfaces affect the transfer of charge is the central one in most investigations on this subject, and it would be impossible to summarize the experimental findings of the various workers here, more especially as there has been a considerable amount of contradictory results reported. What can usefully be done is to list and comment on the mechanisms that have been proposed to describe the phenomena. In doing so we must recognize that most, if not all, the proposed mechanisms are plausible and may actually apply in particular cases, and that several effects may occur at once. It is a commentary on the state of our knowledge that we cannot as a rule say with any certainty whether the phenomena under discussion are equilibrium or kinetic effects. The author, indeed, believes that much of the inconsistency in past work has resulted from investigating an equilibrium and a kinetic effect simultaneously without any attempt to separate them.[15]

MECHANISMS

Some which have been suggested are as follows:

(*a*) An equilibrium effect depending upon the different affinities of the two surfaces for the charged particles. This is usually known as the Helmholtz[16] hypothesis, and, when applied to electrons, corresponds to the phenomenon of contact potential between two metals. (Harper[13] has shown how, when two metallic bodies are brought together and separated without sliding contact, the charge produced on one of them can be quantitatively explained on the assumption, among others, that it arises from the contact potential only.) On this hypothesis a "double layer" is formed *astride* the boundary between the two surfaces as soon as they come

together, and is split when they are separated. The effect of any rubbing that may take place between the surfaces would, on this hypothesis (as with any postulated equilibrium effect), be to increase the areas of the surfaces which have come into actual contact, and perhaps also to change the nature of the surfaces by strain or the rubbing away of surface films.[19]

(*b*) An equilibrium effect depending upon the different abundance of a particular kind of charged particle on the two surfaces. The author has not seen this put forward explicitly as a theory of charge separation, but it is implicit in the explanations which have been given, for example, of the effects of acidity and alkalinity of surface on the sign of electrification.[17] A difference in numbers of a given kind of ion on the two surfaces could cause a net charge to be transferred in a direction opposite to that of the transfer which would be predicted on grounds of relative affinity alone. To take a hypothetical example, suppose that one surface has an acidic group for every 10 Å^2. When the surface is electrically neutral, there will be 10^{15} potentially mobile hydrogen ions and the same number of fixed negative groups per cm^2. If the second surface has initially no hydrogen ions, and has less affinity for them, so that an expenditure of work w is required to move one ion from the first surface to the second, then at equilibrium approximately $10^{15} \exp(-w/kT)$ ions will have transferred to the second surface per cm^2. If w is, say, 0·20 eV, then at room temperatures there will be approximately $3{\cdot}7 \times 10^{11}$ ions/cm^2 or a positive charge of 180 e.s.u./cm^2 on the second surface, although the latter has less affinity for the ions than the first surface. This concentration effect is in some ways analogous to the Peltier effect in metals. The latter gives rise to potential differences smaller than the contact potentials by several powers of ten, but this is because the effective concentrations of electrons capable of changing their energy in metals do not bear large ratios to each other. Two surfaces of non-conductors may have vastly different numbers of a given kind of ion on them, with the result that the concentration effects become more important.

(*c*) A kinetic effect due to the formation of a "double layer" *on one side of* the boundary. This double layer is supposed to exist normally on one of the surfaces before contact is made with the other, and the effect of friction between the two is to cause the top layer to be partially skimmed off on to the other surface.[20,21] This is an old hypothesis which was in its early days expressed in ways which we should nowadays consider crude. Perhaps a more modern version would be to envisage ionizable groups forming part of one surface, which are not ionized for lack of polar bodies to accept the ions and reduce the energy of ionization to a level at which thermal motion could bring it about. The other surface might provide the necessary polar bodies and sweep away some of the ions of one sign, thus becoming charged.

(*d*) Electrochemical effects.[17,18] It is not easy to make a clear distinction between this type of hypothesis and the Helmholtz theory. Perhaps the distinguishing feature of the electrochemical theory is the postulation of a film of electrolytic material (e.g. adsorbed water) between the surfaces.

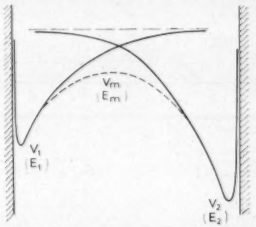
(*e*) An equilibrium phenomenon due to the piezoelectric effect.[22] This can apply only to crystalline, or at least molecularly orientated, surfaces. Pressure between the two surfaces is supposed to produce polarization of parts of one of them. This by itself would not result in an overall charge on the surface, but leakage of charge to one or other end of the crystallites through a poorly conducting medium under the influence of the field set up by the polarization could produce such a charge. Such a theory has been used by Martin[22] to explain some curious phenomena observed with wool fibres.

(*f*) A pyroelectric effect produced at hot spots as the result of friction.[22,23] Presumably this could only happen on a crystalline surface, and the same considerations apply as to the previous theory, except that this is a kinetic theory involving friction, whereas the piezoelectric theory only required static pressure.

(*g*) A kinetic effect due to the thermal *gradient* across the interface, following from asymmetric rubbing, has been postulated by the author in another contribution in this Supplement.[15] The thermal gradient would encourage the motion of mobile particles of whatever nature from hot to cold, and if the particles were predominantly charged with one sign, a separation of charge would occur. There is no need to discuss this further here, except to point out that since asymmetry is introduced in the rubbing process there is no need for the surfaces to differ in their nature. Phenomena of this kind have been observed,[15,24] and the author believes them to be of general occurrence.

AN ILLUSTRATIVE THEORY

Finally, we will give a simple and relatively crude form of quantitative theory, not so much in the hope that it will apply to any actual case as by way of illustration of the way in which several of the mechanisms listed above may act together. We will suppose that only one type of mobile particle is concerned, and that it will be sufficiently accurate to use classical mechanics. This last assumption is probably true if we are dealing with atomic ions, though not if electrons are concerned. We shall ignore surface structure, and the treatment will have much in common with that used for electrochemical potentials by Butler.[25]



Potential energy of charged particle between two insulating surfaces

Let there be two surfaces (see figure), denoted by subscripts 1 and 2, situated at a distance D apart. Let the potential energy of a charged particle approaching either of these surfaces alone, and in the absence of an external electrostatic field, be as shown in the two full curves in the figure. At distances large compared with atomic dimensions the potential energy will mainly be controlled by the "image" forces, but when the ion comes close to the surface there will be a sudden increase of repulsive forces, giving rise to a minimum potential energy, at the equilibrium position, of V_1 or V_2, as shown in the diagram. When the surfaces are close together, we may expect the two individual curves to be joined, as shown dotted, giving rise to a maximum potential energy for the ion, at the position of unstable equilibrium, of V_m.

If the number of ions per unit area of surface 1 is n_1, and

T_1 is the temperature, then we have for the number of ions per second leaving surface 1, and passing over the potential barrier to surface 2:

Rate of loss of ions from surface 1

$$\propto n_1 T_1^{\lambda} \exp\left(-\frac{V_m - V_1}{kT}\right) \quad (1)$$

The exponent λ has varied from $\frac{1}{2}$ to 2 in expressions of this type in the past according to the type of statistics employed, and will also depend upon whether the ions can pass freely into the surfaces or, as we have assumed, can only vibrate about an equilibrium position. We need not commit ourselves here as to its value. Quantum mechanics would assign a less simple energy distribution function than the plain exponential, but the latter will serve our purpose.

For the rate of passage of ions in the reverse direction there will be a similar expression with the subscripts 1 changed to 2. The two rates will in general be different, and hence there will be a net passage of ions in one direction, with the result that charges will build up until the ensuing electrostatic field equalizes the rates at which the ions pass in the two directions.

Let the electrostatic potentials at the equilibrium positions of the ions on the two surfaces be E_1 and E_2, and the electrostatic potential at the position of maximum total energy be E_m. We will now denote by V_m the value of V at the position of maximum *total* energy, which may differ slightly from the value used in equation (1). Since we shall not use the latter again, this will not matter.

We now have to allow for the electrostatic potential energy of the ions in the exponential functions, and we have for the steady state, when the rates of passage will be equal in the two directions:

$$n_1 T_1^{\lambda} \exp\left[-\frac{V_m - V_1 + e(E_m - E_1)}{kT}\right] = n_2 T^{\lambda} \exp\left[-\frac{V_m - V_2 + e(E_m - E_2)}{kT}\right] \quad (2)$$

where e is the electronic charge. We have assumed different temperatures on the two sides to allow for the temperature gradient due to asymmetric rubbing.

If there be applied an external electrostatic field of magnitude F in addition to that due to the net charge densities $\pm\sigma$ on the two surfaces we shall have

$$E_1 - E_2 = eD(4\pi\sigma + F) \quad (3)$$

Also we may write

$$V_1 - V_2 = W_2 - W_1 = \Delta W \text{ (say)} \quad (4)$$

where W_1 and W_2 are the amounts of work required to remove the type of ion concerned from the surfaces into a vacuum.

Taking logarithms of equation (2), rearranging, substituting for equations (3) and (4), and writing $V + eE = U$, $\frac{1}{2}(T_1 + T_2) = T$, and $T_2 - T_1 = \Delta T$ (assumed small compared with T), we eventually get

$$4\pi eD \,.\, \sigma = -\Delta W + kT \log \frac{n_2}{n_1} - eDF + \frac{\Delta T}{T}\left(\lambda kT + U_m - \frac{U_1 + U_2}{2}\right) \quad (5)$$

The term $-\Delta W$ represents the difference in affinity of the two surfaces for the particle in question. It corresponds to the Helmholtz hypothesis, or to the contact potential between metals, and represents mechanism (*a*) on our list.

The term $kT \log (n_2/n_1)$ is the "abundance effect" described under (*b*) in our list. As an example of its value, if $n_2/n_1 = 1000$, it comes to about 1/6th of an electron-volt at room temperature.

The term $-eDF$ represents the effect of the external field, and we see that it gives rise to an additional charge density sufficient to produce an equal but opposite field between the surfaces. This is virtually the conclusion which Medley[1] reaches as the result of experiment.

The term in $\Delta T/T$ represents the effect of the temperature gradient due to asymmetric rubbing—mechanism (*g*) in our list. The first term inside the brackets shows an effect similar to that of thermal diffusion and corresponding to the Thompson effect in metals. The remaining terms inside the brackets are a measure of the potential energy "hump" which has to be surmounted by particles of the given type in crossing from one surface to the other. This will increase with the instantaneous value of the distance between the surfaces, but if it gets too large compared with kT, the rate of transfer of particles would become too slow for our initial assumption of a steady state to apply, depending upon the rate of motion of the surfaces. More consideration would be needed to apply the theory to any particular case, but we need not go further for our present purpose.

We have neglected any change of affinity with temperature; this would have appeared as another term within the brackets, but is probably insignificant.

The reader is reminded that the above theory is probably too crude to apply to any actual case, and is merely intended to be illustrative. It does not in any way deny the possible existence of mechanisms (*c*), (*d*), (*e*) and (*f*) in our list; these might come in as additional effects.

ACKNOWLEDGEMENT

The author is indebted to the Director and Council of the British Cotton Industry Research Association for permission to publish this paper.

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DISCUSSION

Dr. G. Morris: I consider that the concepts of conductors and insulators could be usefully replaced in "static" problems by a concept now common in, for example, control theory. Every arrangement has a rate conditioning combination of capacitance and resistance, and it is the ratio of the intrinsic time of the experiment to the time constant which regulates the performance of the apparatus.

Author's reply: The point is a very sound one, particularly in the discussion of "static" on material passing through a machine—a question which I discuss at greater length in my paper on electrostatic eliminators in the textile industry presented to this conference (see p. S 78). The idea of the leakage time of a homogeneous dielectric being independent of its geometry is of course familiar; the concept might require some adaptation to take account of surface leakage.

The electrification of fluids in motion*

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The electrification of electrolytes by flow in pipes can be explained in terms of the Helmholtz electrical double layer, and it is suggested that some sort of double layer is also produced in commercial grades of organic liquids, such as petroleum, by impurities. The charge produced is expressed in terms of the electrokinetic potential and the Reynolds number. With an immersed discharge electrification will not be observed unless the resistivity exceeds about 10^{11} Ω cm. It is pointed out that the theory is closely associated with hydrodynamics and that in experiments the requirements of dynamic similarity must be observed if important scale effects are to be avoided, and the theory is extended to charges formed on filters and in washing fabrics. Such published experimental work as is available is consistent with the theory set out.

The electrification of drops, spray and wet steam is also discussed briefly.

1. LIST OF SYMBOLS

μ = refractive index of light
M = dipole moment (of molecule)
Q = electric charge
I = current
C = capacitance
V = electrical potential or potential difference
K = dielectric constant (specific inductive capacity or permittivity)
ρ = electrical resistivity
χ = thickness; thickness of Helmholtz electrical double layer
ζ = electrokinetic or zeta potential
σ = surface density of electric charge
s = volume density of electric charge
u = velocity
$\bar{u}$ = mean velocity
η = viscosity
ω = density
l = length
d = diameter
r = radius
p = fluid friction (viscous drag per unit area).

* Any opinions expressed are those of the author personally and do not necessarily represent the official views of his department.

2. INTRODUCTION

The following study of the generation of electrical charges in moving fluids was completed about 1937 and was included in a monograph on frictional electricity prepared by the author towards the end of the late war and circulated privately, but it has not previously been published. The present summary of the results is intended to be read in conjunction with a companion paper presented to this conference and entitled *The practical estimation of electrostatic hazards* (see p. S 71).

3. NOTATION AND UNITS

Some compromise in the symbols used has been necessary because results have been taken from electrostatics, hydrodynamics and surface chemistry and the symbols used in the standard works on these subjects differ and overlap.

The writer has found that the best way to avoid confusion of units is to do all *theoretical* work in electrostatic units and C.G.S. mechanical units. This avoids the frequent occurrence of awkward coefficients such as 9×10^{11}. It is common American practice to refer to C.G.S. electrostatic units as stat amps, stat ohms, etc.

4. THE DOUBLE LAYER, ELECTRIFICATION BY FLOW

The electrification of aqueous solutions has been fairly satisfactorily explained on the basis of the double layer theory,

first put forward by Quincke and Helmholtz to account for cataphoresis, electro capillarity and osmosis. Briefly they assumed that the liquid-solid or liquid-gas interface was electrically polarized, and had a bound layer of charge on the surface and a free layer of charge at a very small distance within the liquid. These two layers resemble the plates of a condenser and it follows that $\zeta K = 4\pi(\sigma\chi)$ in e.s.u. which is used in the Appendix to derive equation (1) below.*

Any movement of the liquid which causes a slip between the fixed and free charges causes a flow of electricity and possible

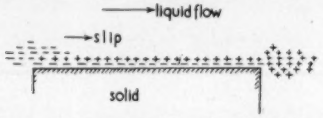

Fig. 1. Charge separated by slip of double layer

accumulation of charges at the two ends as indicated in Fig. 1. If the liquid is flowing through a pipe the rate of flow of electricity is

$$I = \tfrac{1}{4}NF(K\zeta)\bar{u} \qquad (1)$$

where $N = \bar{u}d\omega/\eta$ is the Reynolds number and $F = p/\omega\bar{u}^2$ is the Reynolds coefficient of resistance. The independent variable is the mean velocity $\bar{u}$; N is calculated and F can then be obtained from curves given in standard works on hydrodynamics.

Disregarding any leakage through the apparatus, stability is reached when the "transport current" equals the returning conduction current, i.e. when $V = I(4l/\pi d^2)\rho$ *if the outflow from the pipe is submerged*, V being the voltage between the two ends of the pipe. Since I is likely to be of the order of 10^{-8} A or thereabouts, it is clear that a dangerous potential difference will not arise unless $\rho l/d^2$ is of the order of 10^{10} or higher. It is thus clear that in most circumstances danger is only to be expected in handling liquids with a high resistivity; but there must, on the other hand, be *some* ionization to produce a double layer. Dissociable liquids usually have a relatively high molecular dipole moment which is indicated by K differing significantly from μ^2 (see Table 1).

Table 1. *Physical constants of typical liquids*

Liquid	μ^2	K	M	*Remarks*
benzene	2·25	2·27	0	Undissociated
paraffins	2 (approx.)	2 (approx.)	0	Undissociated
water	1·78	80	1·84	Strongly ionized
ethyl ether	1·80	4·7	1·15	Slightly ionized

Water produces large charges but they are rarely noticed because its relatively high conductivity allows them to leak away. Ethyl ether is one of the most dangerous liquids to handle because of its propensity to produce charges. Benzene and paraffin should produce no charges and the writer has read reports which state that this is so for chemically pure material, but it is certainly not true of commercial and most laboratory samples. The explanation appears to be that commercial paraffins, etc., always contain some dissolved water and other electrolytic impurities which are sufficient to give a measurable, though very low, conductivity. Ions appear to be adsorbed on to aggregates of molecules and are also, presumably, adsorbed at all surfaces, thus producing some sort of double layer. There is a good deal of indirect evidence supporting this hypothesis.

Charges may also be liberated at discontinuities in the manner illustrated in Fig. 2. At the bump, part of the free charge may well be swept from the double layer to form a

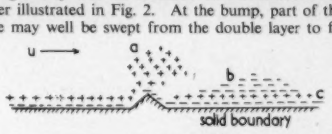

Fig. 2. Transient charges liberated at discontinuity (remixed by turbulence)

a, free positive charge swept away; *b*, free negative charge released by formation of new positive charge; *c*, new free positive layer.

moving space charge, but a new double layer will immediately be formed on the down-stream side together with a second space charge of the opposite sign. Such free charges will usually be rendered innocuous in a short distance by turbulent mixing. Similar considerations apply to diffuse charges formed by any general roughening of the pipe walls. With either small pipes, viscous liquids or low velocities, however, the flow may be streamline and the charges persist unmixed (see Appendix), but although some extensive series of experiments have been directed to their detection it is very difficult to see how they could become important or dangerous.

A space charge of one sign only, which cannot therefore be rendered innocuous by turbulent mixing, will be produced when there is a charge in ζ owing for example to a charge in the material of the pipe wall; this will die away according to the relaxation law given in the Appendix.

5. RELAXATION

It is well known that a bulk charge in a homogeneous liquid will diminish according to the following law

$$s = s_0 \exp(-4\pi t/K\rho) \text{ in e.s.u.} \qquad (2)$$

which is independent of the geometry of the charge and surroundings; if there are charges of opposite signs they will neutralize one another, otherwise they will diffuse to the surface and be distributed there in such a way as to minimize the potential energy as for an ordinary conductor. It is shown in the companion paper that unless $K\rho$ is large, i.e. ρ is greater than about $10^{11}\ \Omega$ cm, any charge will be relaxed almost instantaneously and for this reason the separated charges in Figs. 1 and 2 recombine far too quickly to be observed when the liquid is water or an aqueous solution, unless the outflow breaks up into drops and is collected in the form of spray.

A number of conclusions of considerable practical importance follow immediately from this result, but they have frequently been overlooked, for example:—

(i) If charged liquid is collected in an earthed container and $K\rho$ is low, the charge is, of course, immediately lost, but if it is collected in an open insulated container it behaves as a charged *conductor* and earthed conductors must not be brought near it. Any material whose resistivity is below, say, 10^9 or $10^{10}\ \Omega$ cm is as good (or bad) as a perfect conductor in such conditions and sparks have been drawn from a person's fingers—or even a batten of soft wood—in dry cleaning and the preparation of rubber solution, etc., causing serious fires.

* The free layer is now thought to be more in the nature of a diffuse space charge and the constants have only a statistical meaning at molecular distances, but the two products ζK and $\sigma\chi$ have fairly definite values which have been determined experimentally and the simplest form of the theory is sufficient for the present purpose.

(ii) Since the relaxation rule is independent of the geometry of the situation stirring, which has frequently been recommended, will not hasten the discharge, and extra charges may be separated by the movement of the stirrer, particularly at sharp edges and these may cause a spark when it is withdrawn.

Agitation may distribute a local concentration of charge, but agitation by compressed gas is dangerous since the bursting of bubbles produces large charges.

6. FILTERING AND DRY CLEANING

If we adopt as a working model of a filter, a bank of fine capillary tubes then it can be shown (see Appendix) that the maximum total charge which can be built up on the filter (or carried away in the liquid) is

$$Q_{max} = n/2\pi(K\rho)(K\zeta)\hat{u} \qquad (3)$$

where n is the number of tubes. If an experimental constant is substituted for $n/2\pi$ this should give the charge per ft^2, for example, at any speed of filtering. The charge on the filter will be established fairly quickly and after this filtered liquid will come away practically uncharged.

A considerable number of fires occurred in dry cleaning before the use of low flash-point liquids was prohibited in this country. The action is much the same as for filters, and sparks and fires are liable to occur when the charged garment is lifted out of the fluid. If ρ is reduced to below about $10^{11}\ \Omega$ cm by the addition of soaps or alcohols, etc., measurable electrification can be completely prevented, but there are practical difficulties because the conductivity becomes "exhausted" after a time (Hartshorn and Ward). This is a further example of the relaxation rule (see Section 5 above).

In dry cleaning, fires were sporadic and irregular in incidence, the explanation probably being that, as well as ρ varying considerably, ζ would depend almost entirely on the nature of adsorbed surface films, i.e. on the kind of "dirt" which was being removed.

7. EXPERIMENTAL PROCEDURE

It is only in the case of flow through pipes that the rate of electrification can be expressed in terms of well-known results. In all other cases values must be obtained experimentally. It is important, therefore, to remember that the study of the electrification of fluids in motion is a branch, or extension, of hydrodynamics and that unless the requirements of dynamic similarity are appreciated, useful results cannot be obtained. In high-speed flight, the resistance of ships, etc., experiments are made on dynamically similar models and the experimental results expressed in zero dimensional terms—such as the Reynolds number and Mach number. All the equations given in this paper can be expressed as particular examples of a general equation of this type, i.e.

$$\psi\left[\left(\frac{ul\omega}{\eta}\right), \left(\frac{p}{\omega u^2}\right), \left(\frac{K\zeta l}{Q}\right), \left(\frac{K\rho u}{l}\right)\right] = H$$

where H is a number obtained experimentally. It should be noted that $(K\zeta)$ and $(\sigma\chi)$ are interchangeable and sl^3 can be substituted for Q; potential $V = Q/C$ is dimensionally the same as Q/lK. The correct procedure is to construct a scale model and in any one set of experiments to keep three of the terms constant while varying the fourth, to obtain sets of curves such as $\psi'(K\rho u/l) = H'$. Unless this is done undesirable "scale effects" will appear. If the conditions are observed, however, results with one liquid or apparatus can be applied to others. The matter is discussed in detail by Johansen.

8. VERIFICATION

In the preceding paragraphs a fairly complete theory has been set out for the electrification of fluids in movement. As stated, only a few of the reported experiments give sufficient detail for calculations to be made, but in one or two cases it is possible to compare the results with the theory and these are given below.

(*a*) Mackeown and Wouk measured the current conveyed into an insulated road tanker from a petrol supply pipe. The physical constants of the liquids are not given, but if we assume that $K = 5$, $\eta/\omega = 0{\cdot}01$ and, for want of any definite information that $\zeta = 0{\cdot}05$ V and taking appropriate values of N and F for a 2 in. brass nozzle (tube),* the following calculated results are obtained.

Table 2. *Calculated charging currents in petroleum*

Flow	*N*	*F*	*I*
100 gal/min	200 000 (approx.)	0·0025	$1{\cdot}35 \times 10^{-8}$ A
500 gal/min	1 000 000 (approx.)	0·0015	20×10^{-8} A

Fig. 3 shows the experimental results they obtained and it will be seen that though these differ considerably one from another, the average values agree with the calculation.

(*b*) Hartshorn and Ward carried out a number of experiments to ascertain under what conditions garments acquired charges during dry cleaning, and whether this could be prevented by increasing the conductivity of the spirit. They found that charges could not be detected if the resistivity were below $10^{11}\ \Omega$ cm. This agrees with an earlier result of Richter, and with the relaxation rule (see Section 5).

(*c*) In a German report of which the writer has an abstract but not full particulars, a charge which appears to have been generated at a discontinuity was detected in a petrol pipe line but disappeared before reaching a second sampling point further along, as was to be expected.

(*d*) In some experiments on fluids pumped at 2 gal/min through a ¼-in. rubber hose no charge accumulated with 95% ethyl alcohol or diacetone alcohol, but substantial charges were obtained with xylol. The alcohols are moderate to good conductors and xylol a near insulator. It also appears that Holde, experimenting with benzene of resistivity 10^{14} and $10^{15}\ \Omega$ cm, obtained substantial charges, as did Dolazalek with $10^{12}\ \Omega$ cm, while Richter, using a liquid of resistivity $10^7\ \Omega$ cm, failed to obtain bulk charges, these results again agreeing with the relaxation rule.

(*e*) The writer has seen references to the production of charges by straining petrol through chamois leather, but as the strainer would not be fully flooded on both sides the relaxation rule may not be fully applicable. Apart from this he has been unable to trace any data on filters.

These results all tend to confirm the theory that has been developed, but further work, properly controlled, is desirable.

9. ELECTRIFICATION OF DROPS AND SPRAY

Whenever the surface of a liquid is violently disturbed there is a tendency for electrical charges to be formed. This occurs, for example, when bubbles burst or when spray is formed. One example, on which Simpson has made carefully controlled experiments, is the breaking up of drops of water on striking a metal plate. J. J. Thomson pointed out that only one part in thirty million of the charge in the double layer need be liberated to provide the charges obtained, and some years ago

* From curves given by Stanton and Pannell (see bibliography).

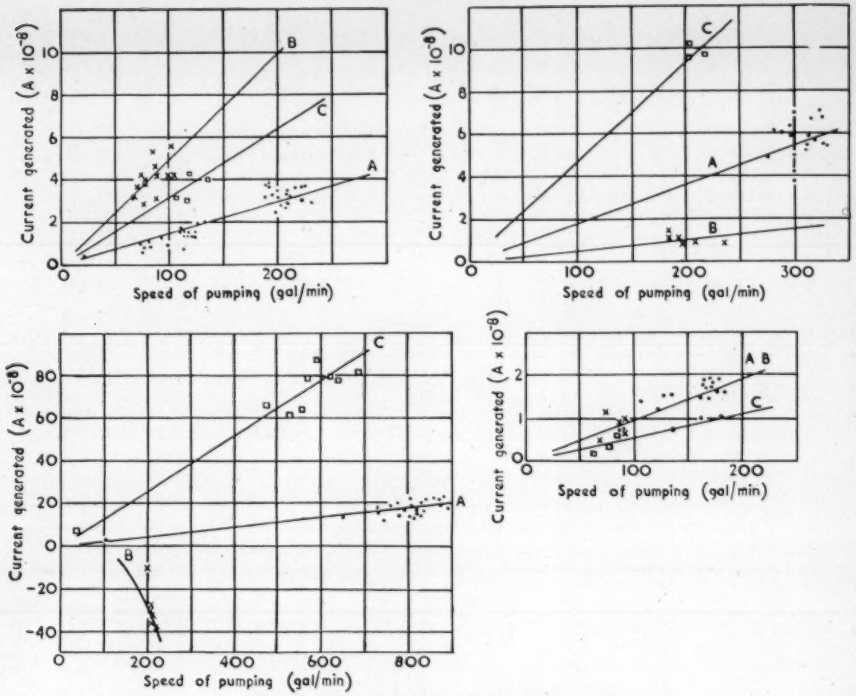

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Fig. 3. Currents produced by flow of petroleum of different brands [MACKEOWN and WOUK]

the writer noted that this could arise from the difference in area between the inner and outer layers on the assumption of equal density of packing, and on this basis $\delta Q = 8\pi r\chi\sigma$. Values of $(\chi\sigma)$ obtained from cataphoretic measurements on bubbles in water vary according to the degree and type of dissolved impurities, but are of the order 4×10^{-13} coulomb cm, that is $\delta Q = 10^{-11}\, r$ coulombs (approx.). If we assume for simplicity that each drop is split into n equal drops then the extra out of balance charge which might become available is $Q' = (n^{\frac{1}{3}} - 1)r \times 10^{-11}$ coulombs and for $n = 8$ this gives:

r cm	*Coulombs calculated*	*Coulombs observed*	*Remarks*
0·39	$11{\cdot}7 \times 10^{-12}$	$2{\cdot}8 \times 10^{-12}$	Simpson—drops striking metal plate
0·24	$7{\cdot}2 \times 10^{-12}$	$0{\cdot}8 \times 10^{-12}$	Hochschwender, quoted by Guest—drops broken up in air stream

The results are of about the same order of magnitude and there may be some connexion, but no mechanism has yet been suggested which would satisfactorily explain what happens. There may also be a connexion with the variation of surface energy for drops of different sizes.

The best known example of the electrification of droplets is probably that of the charges produced by wet steam when blown through a nozzle or small crack. This was first observed on a locomotive at Sedgehill near Newcastle and was investigated by Mr. (later Lord) Armstrong in 1840. With an experimental boiler, suitably insulated, dense sparks up to 22 in. long were produced.

APPENDIX

Pipe flow

The capacity of a cylindrical condenser diameter d, length l and separation χ, is

$$C = Kdl/4\chi$$

Charge per unit length for potential difference ζ between plates is

$$Q = \zeta Kd/4\chi$$

Transport current due to slip of inner layer at velocity u_t

$$I = Qu_t$$

Assuming streamline flow at the boundary and uniform velocity gradient through small thickness χ

p = viscous drag per unit area

$$= \frac{\text{coeff. of viscosity} \times \text{velocity diff.}}{\text{thickness}}$$

$$= \eta u_t/\chi$$

Substituting these results in the formula for I and multiplying top and bottom by $\omega\bar{u}^2$ where ω = density and $\bar{u}$ = mean velocity in pipe we obtain

$$I = \tfrac{1}{4}(\zeta K)\left(\frac{\bar{u}d\omega}{\eta}\right)\left(\frac{p}{\omega\bar{u}^2}\right)\bar{u}$$

The advantage of writing the result in this form is that it is shown in treatises on hydrodynamics that

$$\frac{p}{\omega\bar{u}^2} = \psi\left(\frac{\bar{u}d\omega}{\eta}\right)$$

values of ψ being obtained experimentally except for completely streamline flow, in which case it can be proved theoretically that

$$\left(\frac{\bar{u}d\omega}{\eta}\right)\left(\frac{p}{\omega\bar{u}^2}\right) = 8$$

and therefore $I = 2\bar{u}\zeta K$.

Filters

If there are n tubes in parallel and they are all completely immersed in the liquid equilibrium will be reached when I_n equals the rate of relaxation, i.e. when

$$\frac{dQ}{dt} = (4\pi/K\rho)Q$$

so that

$$2n\bar{u}\zeta K = 4\pi Q/K\rho, \text{ i.e. } Q = (n/2\pi)(K\rho)(\zeta K)\bar{u}$$

With an experimental constant in place of $n/2\pi$ this will give the equilibrium charge on the surface of a filter.

Discontinuities

The charge produced by a discontinuity or obstruction in a pipe, as indicated in Fig. 2, will die away according to the relaxation law

$$s = s_0 \exp(-4\pi t/K\rho) = s_0 \exp(-4\pi l/K\rho\bar{u})$$

which gives the *mean* density of charge at points down stream but, as explained, the opposite charges will often be thoroughly mixed by turbulence and rendered innocuous long before they have actually reunited.

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LORD ARMSTRONG's experiments and other work on electrification of steam are described very fully in an old book by J. H. PEPPER, *Chemistry, Electricity and Light.*

DISCUSSION

Dr. G. Morris: Mr. Cooper stated that electrostatic units are "right and proper units" for static study. It occurs to me that the ordinary units of volts, ohms, etc., are to be preferred since the magnitudes are immediately apparent.

Author's reply: Dr. Morris objects to my assertion that C.G.S. electrostatic units are the natural ones for electrostatic studies. There are two answers to this. In the first place it happens that the quantities to be measured give small numbers when measured in this system. If volts, amps, etc., are used, one is continually plagued with multipliers such as 9×10^{11} which I find confusing. In the second place, considerable use has to be made of the classic treatises on electrostatics and hydrodynamics and the formulae found in them are all in C.G.S. units and I find I am less liable to arithmetical blunders if in *theoretical* work I stick to one set of units at a time. After all, electrostatic units were devised by the early physicists presumably because they were convenient for the results they obtained. If the power from a Wimshurst machine had amounted to meggawatts their choice might have been different.

Electrification by freezing

By E. W. B. Gill, M.A., B.Sc., Clarendon Laboratory, University of Oxford

The high potentials of the order of 100 V developed when ice is formed from dilute solutions were investigated to discover the mechanism.

Contact potentials between solids and liquids are usually of the order of 1 V and some further fact must operate to achieve 100 V.

The theory suggested is that, whereas in the usual case the charges producing the potentials are adjacent to the boundary, in the case of freezing ice the charges extend to a small distance from this boundary.

1. Introduction

A few years ago it was discovered in the U.S.A. that surprisingly large potentials—sometimes exceeding 200 V—were developed when dilute aqueous solutions were frozen. The ice in the majority of cases takes a positive potential and the liquid a negative one.

The chief work was done by Workman and Reynolds,* who found that this potential only occurred while freezing was taking place and that nothing occurred if the freezing stopped or melting began. The magnitude depended on the concentration and the nature of the solute. They also noted that the potential was capable of maintaining small currents of up to about 1 μA. Beyond suggesting that the effect was due to an excess of positive ions being frozen into the ice, no precise explanation of the mechanism was given. The following experiments were conducted to throw more light on this phenomenon.

2. The experiments

The solutions were always made up from very carefully distilled water, and freezing was effected by means of a copper rod bent twice at right angles, one end dipping into liquid air and the other end into the solution. Provided the liquid air level was kept constant this gave an almost uniform rate of ice production. Copper rods of different cross-section gave different rates of production. All the results to be quoted were, unless otherwise stated, obtained with a copper rod of circular cross-section and of 1 cm diameter, immersed 5 cm in the solution which produced about 2 c.c. of ice per minute.

The ice formed a circular solid cylinder round the copper, 5 cm long, with a hemi-spherical lower end. Its width decreased slightly from the top, down the first 5 cm. The potential was measured between the central copper and an electrode immersed in the solution, using an electrometer triode valve and a null method.

3. Open-circuit potentials

Whatever the solute the results followed the same pattern. Except for very dilute solutions no appreciable potential resulted. The critical concentrations below which measurable potentials occurred were different for each substance. As the concentration was reduced below this critical value the potentials steadily increased, reached a maximum and then, for extreme dilutions, decreased; and all indications are that with absolutely pure water no potential would occur. As soon as a layer of ice completely covered the copper a potential difference was registered which increased rapidly at first, gradually slowing down, until in general, after 20 min, there was still a slight increase.

At first it was not possible to get reproducible results; the cure was slowly to rotate the beaker containing the liquid, which was equivalent to constant stirring. With this precaution fairly consistent results were obtained. Table 1 is an example of the rate of growth of the potential.

Table 1. *Solution of ammonium hydroxide, concentration 10^{-5} normal. Ice positive, liquid negative*

Time (min)	2	4	6	8	10	12	14	16	18	20
Potential (V)	35	45	53	60	65	70	74	77	80	82

If at any stage the system is short-circuited for a minute or two the voltage sinks to zero; and if the short-circuit is removed the growth curve is almost identical with the original. If the short-circuit is only momentary, some drop in potential occurs but not to zero; and then the usual rate of growth from this new starting-point is resumed. The rates of increase of potential seem almost identical for different concentrations so that the potentials after the same time of freezing give a comparison of the effect of concentration.

Table 2. *Voltages measured after 20 min for ammonium hydroxide solution*

Concentration (normal)	10^{-4}	5.10^{-5}	10^{-5}	2.10^{-6}	5.10^{-7}	10^{-7}
Potential (V)	0	24	82	88	68	19

It will be seen that the range of concentrations over which voltages occur is somewhat limited. For other substances it may be much larger; an example is potassium permanganate, the data for which are given in Table 3.

Table 3. *Voltages measured after 20 min for potassium permanganate solution*

Concentration (normal)	10^{-2}	5.10^{-3}	10^{-3}	10^{-4}	2.10^{-5}	10^{-5}
Potential (V)	15	30	45	100	115	5

Quite a strong concentration (around N/10) is necessary to make the potential inappreciable, and it is only at this concentration that the ice is really coloured, for all the other concentrations it is practically uncoloured and undistinguishable to the eye from ice formed from distilled water. The solution has, of course, a strong colour.

When this experiment was repeated with a copper rod giving double the rate of ice production, the potentials at the corresponding times were considerably larger, suggesting the potentials increase as the rate of freezing increases.

An example of a substance giving a small potential is copper sulphate for which the results are given in Table 4, the three values in bold type being approximate.

* Workman and Reynolds, *Phys. Rev.*, **78**, p. 254 (1950).

Table 4. *Voltages measured after 20 min for copper sulphate solution*

Concentration (normal)	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Potential (V)	0·5	0·65	**4**	**10**	**10**

The results with these substances suffice to give the general picture and it is unnecessary to quote other substances tried. In all cases the ice was positive with respect to the liquid. No experiments were done with the few substances quoted by Workman and Reynolds as giving reversed polarity.

4. POTENTIALS WHEN SOLUTION IS SHORT-CIRCUITED

The rate of growth of the potential between the ice and the liquid was next measured when the electrode was connected back to the central copper, through various large resistances; the arrangement was, in fact, like a cell providing current which flowed through the external resistance and back through the ice. For the biggest resistance used (11 000 MΩ) the growth curve was similar to that in open-circuit, the voltages being slightly lower. But for external resistance from, say, 500 to 50 MΩ the growth only took two or three minutes; the potentials then became constant for a time and later fell slowly, the value after 20 min being around 80% of the maximum.

What is important is that over the range of external resistances of 50 to 500 MΩ the potentials were, within experimental error, proportional to this resistance for the same times of freezing; that is, the currents were identical. It is evident that this cannot be true for all higher resistances, as that would involve an infinite potential in open-circuit. The currents thus fall off as the resistances are much increased. The current for the lower resistances gives an estimate of the maximum transfer of charge from the liquid to the ice; the value depends on the concentration. Thus for a potassium permanganate solution the currents were approximately $\frac{1}{2}$ μA for concentrations of 10^{-3} and 10^{-4} N, but fell to about one-tenth of this value for 10^{-5} N. These corresponded to charge transfers of 1500 and 150 e.s.u. per sec. As the ice was forming at the rate of 2 c.c. per min the charge transfers were 45 000 and 4500 e.s.u. respectively per c.c. of ice formed. At first sight one is tempted to explain the constancy of current for the lower resistances as one would for a dry cell of constant e.m.f. V and high internal resistance R with a small resistance r across it. Here the current $V/(R + r)$ is little affected by the changes of r if R is very much the bigger.

It is true that the ice resistance is, as will be discussed later, enormous, but this explanation is untenable, for the following reason. If the ice resistance is the determining factor, then as the ice grows it will vary very considerably. After 20 min it will be about four times what it was at 2 min, but the current in that time only decreased fractionally. The tacit assumption that the arrangement gives a constant voltage is thus incorrect and the voltage developed must depend on the current it is giving.

5. THE RESISTANCE OF THE ICE

One clue to what was happening was the variation in the resistance of the ice with change of concentration. The straightforward method of applying different external potentials between the centre copper and the electrode in the solution and measuring the resulting currents was therefore used. The most convenient method was to insert a resistance of the order 10 to 50 MΩ in the circuit and find the current by measuring the voltage drop down it using the electrometer triode. The applied volts less this drop was the voltage drop down the ice, as the liquid resistance from electrode to ice was inappreciable in comparison with the ice resistance. There was, however, the disturbing effect of the potential due to the freezing, which was also in the circuit. The effect of this was that although the plot of current against voltage drop across the ice was a straight line for the larger applied voltages, this line did not pass through the origin and there was deviation from it at the smaller applied voltages. This was bound to be so, because if the applied volts were reduced to zero, the conditions of Section 4 were reproduced and a current flowed which was independent of the external resistance; and in addition, to reduce the current to zero required an applied voltage equal and opposite to the open-circuit voltage. The build-up of potential on freezing being due to positive charge coming in from the liquid, the best chance of consistent results was to apply the external potentials so that the ice was positive to the liquid. All the following results were done with this polarity. In each case the resistances given were the values after the ice had been forming for 20 min. The ice was regarded as a hollow cylinder of inner diameter equal to the external diameter, 1 cm, of the copper rod and the mean outside diameter after 20 min was 2·86 cm. Its length was taken as 5 cm, the curved lower part being neglected. The specific resistance of such a tube is about thirty times the tube resistance between the inside and outside. The results are given in Tables 5 and 6. The resistances being taken from the slope of the above-mentioned straight lines.

Table 5. *Specific resistance of ice in copper sulphate solution*

Concentration (normal)	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Specific resistance (MΩ per cm cube)	700	3800	72 000	77 000	87 000

Table 6. *Specific resistance of ice in potassium permanganate solution*

Concentration (normal)	10^{-2}	10^{-3}	10^{-4}
Specific resistance (MΩ per cm cube)	15 000	50 000	150 000

A word of caution is here necessary. The specific resistance was the mean specific resistance because after 20 min the centre of the ice was about 15° C below zero and there was a temperature gradient across it to 0° C at the liquid surface. The specific resistance rises rapidly as the temperature drops. A rough subsidiary experiment showed it to be roughly four times as much at − 15° C as at − 1° C.

With this in mind no particular significance should be attached to the actual figures of specific resistances given above, but two important facts emerge. The first is that there is a very considerable rise in resistance as the concentration is reduced and this rise commences at the concentration where the open-circuit voltages in Section 3 began to become appreciable. (Workman and Reynolds had also noticed this large change.) The second is the really enormous specific resistances of from 10^{10} to 10^{11} Ω per cm cube attained by weak solutions. Nothing approaching this has been found in any tables consulted. It will be appreciated that measurement of such resistances are not easy because of the possibility of leakage over the top surface of the ice upon which con-

densation and freezing of water vapour in the air is taking place all the time. If such leakage is operative the true resistances are even higher still.

6. SUGGESTED THEORY

The starting point of the suggested theory is the fact stated in Section 3, that when freezing is going on, a permanent current of the order of 1 μA flows if the system is short-circuited by a resistance. The initiation of the current must be at the surface where the freezing is occurring and must certainly be due, as Workman and Reynolds suggest, to a charge separation there. The surface solution contains equal and opposite numbers of charged ions. Either more positive ions are frozen-in than negative, or only positive are frozen-in and no negative. The complete lack of colour of the ice from potassium permanganate suggests the latter is the more probable. Probably at the moment freezing begins the first layer of ice has the same positive ion concentration as the solution, but the potential produced between the ice and the solution by this charge then sets up a force which retards the diffusion towards the surface of the positive ions in the solution and the concentration of the next layer frozen-in is less, and so on. The net result is that only a proportion of the positive ions in the liquid frozen, appear in the ice. As an example of this, with potassium permanganate solution the ions in ice at a concentration of 10^{-4} N have a total charge of 3×10^7 e.s.u., but in the experiments of Section 4 the charge frozen-in was $4{\cdot}5 \times 10^4$ per c.c.

It is suggested that what occurs in open-circuit is this. Successive layers of positive charge are frozen-in, giving a volume distribution in the ice, and an equal amount of negative charge appears in the solution, all concentrated at the liquid ice boundary. The result of all these charges is to set up a field in the ice at all places where there is charge, this field tending to move the positive charges in the ice back to the boundary. How rapidly they move back depends on the ice resistance. The field has a second effect because its size at the boundary determines the amount of charge frozen-in there. So long as fresh charge is freezing-in, the field is increasing and the limit is reached when the field at the boundary prevents any more positive charge freezing-in. In this state of equilibrium, although the charges are leaking through the ice to the boundary, the outward movement of the boundary as fresh ice forms just compensates and the distribution of charge from the boundary inward remains unaltered.

This distributed charge in the ice results in a total potential V between the inside of the ice and its contact with the liquid and a force F at the contact point. Equilibrium is reached when F has some particular value. What is important is that V is not proportional to F and it is not difficult to see from simple electrostatic considerations that if the charge producing F is distributed over a large distance V will be large, but if over a small distance, V will be small. The condition for a good spread is very high ice resistance. This explains the significance of the experimental fact that the big open-circuit voltages correspond with very high ice resistances.

7. MATHEMATICAL THEORY FOR OPEN-CIRCUIT

The open-circuit voltages of Section 3 only increase very slowly after 20 min and it is assumed that soon after this they cease and equilibrium is established. The theory outlined below refers only to this equilibrium condition and does not refer to the previous growth.

For simplicity the ice is supposed to grow on a large flat plate instead of a cylinder and the ice boundary to move outwards at a constant speed of v cm/sec. Take as origin of co-ordinates a point O in the liquid, far enough from the plate to allow the equilibrium to be established before the ice reached there. Let this ice liquid boundary reach O at time $t = 0$ and let Ox be the normal to the plate. Excluding end effects the conditions in all planes in the ice parallel to the plate are the same and depend on the x co-ordinate only and not on y or z.

At the time $t = 0$ there will be a volume density ρ of charge which will be a maximum at the boundary $x = 0$ and which will decrease inside the ice (i.e. as x is increased). The most reasonable assumption is that it decreases exponentially so that

$$\rho = \rho_0 e^{-ax} \tag{1}$$

a being a constant. After time t the boundary has reached the point $x = -vt$ and as the charge distribution from the boundary inwards remains the same it follows that for the two variables x and t the general equation is

$$\rho = \rho_0 e^{-ax} e^{-avt} \tag{2}$$

The application of Gauss's theorem gives the potential distribution across the ice and gives, if V is the total potential and F the force at the boundary,

$$Va = F \tag{3}$$

The potential distribution gives the current i at each point, assuming Ohm's law to hold, and as the excess of current leaving over current entering, in a small volume, alters the charge density the equation resulting is

$$\frac{\partial i}{\partial x} = \frac{\partial \rho}{\partial t} \tag{4}$$

This last equation gives the constant

$$a = 4\pi/RKv \tag{5}$$

where R = specific resistance and K = specific inductive capacity of ice. So finally

$$V = RKvF/4\pi \tag{6}$$

If, as explained previously, charge transfer ceases and equilibrium is obtained when the boundary force F reaches some definite value, the above proves that the open-circuit voltage is proportional to the rate of ice production and also to the ice resistance.

Unfortunately, as F is not known, no numerical check is possible. If F is expressed in terms of ρ_0 the charge density at the boundary, another expression for V is

$$V = (R^2Kv^2/4\pi)\rho_0 \tag{7}$$

Again, ρ_0 is not known, but at any rate the orders of magnitude can be determined. At most it might be the same as the positive ion concentration in the liquid, very likely it is much smaller, but assume the maximum value.

At a concentration of 10^{-4} N the ionic charge per cubic centimetre is 3×10^7 e.s.u. Potassium permanganate solution at this concentration gave 100 V = 1/3 e.s.u. The velocity of boundary movement after 20 min was 1/2000 cm/sec. Taking $K = 80$, the equation gives $R = 0{\cdot}08$ absolute units or $7 \times 10^{10}\ \Omega$. If ρ_0 is less, R is even larger.

It is evident, therefore, that enormous specific resistances are required, but at any rate they are of the same order as those discussed in Section 5. Thus the calculations are consistent with the theory that the potential is due to a volume distribution of charge continuously leaking towards the boundary but keeping pace with the moving boundary. Even with these very high resistances the major portion of the volume charge in the ice is extremely close to the boundary. The distribution $\rho_0 e^{-ax}$ at time $t = 0$ decreases from ρ_0 at the boundary to $\rho_0/1000$ when $ax = 6{\cdot}9$.

In the above case $R = 0{\cdot}08$, $K = 80$, $v = 1/2000$, whence $a = 4000$ and $x = 0{\cdot}017$ mm. (This, incidentally, justifies applying the theory for a flat plate to the cylindrical case.)

At any particular point the volume density drops to one-thousandth of its value in a time t such that $avt = 6{\cdot}9$, i.e.

$$t = 3{\cdot}5 \text{ sec}$$

ACKNOWLEDGEMENTS

The author would like to thank Professor Lord Cherwell for facilities, and Messrs. G. F. Alfrey and N. W. Sanders for help in the research described.

DISCUSSION

Dr. F. J. Scrase: In the experiments which Mr. Gill described the separation of charge occurs between the ice and the solution with which it is in contact. Can this process play any part in the generation of electricity in thunder-clouds, where the ice is formed from droplets? I should have thought that no net charge could result from the mere freezing of the droplets.

Dr. E. C. Craven: The rate of growth of ice in the author's experiments was taken as uniform. In experiments on the bulk freezing of acetic acid, with a constant temperature difference, the rate was found to fall off as the solid layer increased in thickness, presumably owing to the low thermal conductivity of the solid.

In line with the results quoted by Mr. Gill, such bulk freezing is a poor method of purification owing to occlusion of impure mother liquor, and, as with water, dissolved air comes out of solution and is entrapped in the solid, giving it a fictitiously low density.

Liquids giving no electrification by bubbling

By W. R. Harper, Ph.D., F.Inst.P., Imperial College of Science and Technology, London

The contention of Gill and Alfrey that electrification by splashing is due to electrostatic induction in the field of a contact potential is discussed in the light of other published work, and it is concluded that this contention cannot be upheld. The orthodox view that electrification of this kind arises from the existence of a double layer in the vicinity of the liquid surface suggests that there should be no charging with a non-conducting liquid, contrary to what has been found by previous workers. Experiments using the method of bubbling are described which show that the electrification does disappear, even with much more sensitive apparatus than previously used, if the purification of a liquid has been carried far enough to reduce its conductivity to below 10^{-13} mho cm^{-1}. The liquids used were hexane, octane, decane, benzene, xylene, pinene, carbon tetrachloride and a mixture of xylene and carbon tetrachloride. The non-conducting liquids still produce considerable quantities of neutral centres.

Electrification produced by waterfalls, discovered by Elster and Geitel,[1] was explained by Lenard[2] as being due to the disruption of a surface double layer of charge on the water. He originally supposed the negative charge to be in the air, and the positive in the water, but in a later paper,[3] realized that both components of the double layer must be just inside the water surface. Electrification produced by splashing, spraying, bubbling and the shattering of drops, investigated by numerous observers using a variety of liquids (and gases), has generally been attributed to the same cause. This accepted explanation has, however, recently been challenged by Gill and Alfrey.[4,5] They explain their own observations in terms of charging by electrostatic induction arising from contact potentials inevitably present, after the fashion of Kelvin's water dropper.[6] They furthermore suppose other investigators to have been misled when interpreting their own experiments as being in accordance with Lenard's explanation, through having overlooked the importance of the charging of drops when they impinge on and rebound from a solid surface at which there may be a contact potential which can give rise to electrostatic induction. They cite an experiment of Pomeroy[7] on spraying which they interpret in this way, but in doing so make it difficult to understand why the nozzle used in Pomeroy's experiments did not charge up by induction like a water dropper.

Other evidence in support of the orthodox view can be quoted. It may be possible to explain Zeleny's[8] measurements in the way that Gill and Alfrey suggest, but the earlier work of Simpson,[9] referred to by Zeleny, cannot be explained in this way, as Simpson himself showed by a crucial experiment. This demonstrated that the charge thought to have been due to the shattering of drops would have been opposite in sign if it had been due to splashing. Bühl,[10] in experiments on the spraying of mercury, investigated the extent to which electrostatic induction affected his results, and concluded that, though present, it played only a subsidiary rôle. The most convincing argument, however, against the charge being produced by induction in the field of a contact potential, was given by Bloch.[11] Having observed [see ref. (11), p. 100] that a deliberately applied field led to a change in the charging due to bubbling, he then pointed out that the effect observed in the absence of an applied field could not be explained by there being a field present, because no such field could simultaneously lead to the formation of both positively and negatively charged particles, and these were observed in comparable numbers.

Busse[12] discussed whether the positive particles formed in a minority with distilled water could have acquired this charge at the moment of their formation by induction in the field of the more numerous negative particles. This was suggested by Lenard.[3] Busse's opinion was that such was not the correct explanation, but that they were formed from parts of the surface which had just lost negative ions. Coehn and Mozer[13] followed the change in the nature of the charge produced by bubbling as traces of electrolytic impurity were added to conductivity water. At first the resultant

negative charge given to the gas consisted of negative particles only. As impurity was added to the water, positive particles made their appearance, and increased in numbers until the "inversion point" was reached. At this point the resultant charge was zero, but the gas still contained a lot of both positive and negative particles in equal numbers. It seems quite impossible to account for this behaviour in terms of electrostatic induction.

The surface double layer postulated by Lenard itself implies the existence of a contact potential. The evidence quoted above is not to be taken as meaning that charging by induction does not occur. In fact, it must occur. The evidence means that charging due to the mechanical disruption of the double layer is normally much greater. Conversely, the contact potential called upon by Gill and Alfrey, and investigated experimentally for water by Chalmers and Pasquill,[14] implies the existence of a double layer. The double layer is no longer an *ad hoc* postulate introduced to account for waterfall electricity, as implied by Gill and Alfrey, but an inevitable consequence of present-day knowledge about liquids.

The importance of a trace of electrolytic impurity in modifying the charge given by water, confirmed by many workers, suggests that the disruption of the double layer results in electrolytic ions originally present in the liquid being transferred by droplet formation into the gas, some ions remaining attached to droplets, others changing into large or even small ions by evaporation. If this be the mechanism producing electrification in the gas, then no electrification should result when the liquid is non-conducting. Gill and Alfrey[5] point out that decreasing the conductivity of aqueous solutions increases the charge. This was investigated in some detail by Coehn and Mozer,[13] and certainly holds when only a trace of electrolyte is present in the water. Gill and Alfrey[4] got no charging when using transformer oil and carbon tetrachloride in their water dropper experiments. Nevertheless Haner[15] has reported sparks 4 ft long resulting from the industrial handling of transformer oil under circumstances comparable with those of Gill and Alfrey's experiment. Eve[16] investigated a variety of liquids by spraying, and obtained the largest charging with ether, a liquid usually regarded as non-conducting. Apart from mercury, which failed to charge in his experiments, the smallest charge came from sea-salt in water. De Broglie,[17] using the method of bubbling, divided a number of liquids into those which gave charged particles, and those from which he could detect only similar uncharged particles. He was unable to say what characteristic determined the class to which a given liquid belonged. Coehn and Mozer[13] claimed that, with sufficient purification, non-conducting liquids gave negative ions only, and that the extent to which the liquid charged was determined by its dielectric constant. They concluded that "Coehn's Law," which states that when two dielectrics come into contact the one of higher dielectric constant becomes positively charged, should be regarded as having a quantitative significance. They thought the dividing line between De Broglie's active and inactive liquids came at about dielectric constant 5, but that there was really a continuous transition, all liquids giving a recognizable charge. They obtained the smallest charge with ether.

The liquids which Coehn and Mozer called non-conducting were benzene, ether, chloroform, aniline, benzaldehyde, acetone, nitrobenzene and conductivity water, in order of increasing dielectric constant. It occurred to the present author, that this order might also be the order in which traces of electrolytic impurity would supply ions during bubbling. The electrical conductivity of the liquids was not measured by Coehn and Mozer, and the method of purification seems to have been invariably fractional distillation, which may not have been adequate. Indeed this must have been the case: it will appear from the experiments about to be described, that if liquids are sufficiently freed from electrolytic impurity, they give no charge on bubbling.

APPARATUS

Bubblers have been used ranging from that of Busse,[12] which puts a big stream of gas through a large jet with such violence as to make the bubbling more like spraying, to the "Barboteur Villiers" recommended by Bloch,[11] which delivers a multiple stream of fine bubbles. The electrification in which we are interested arises from the surface of the bubbles; small bubbles therefore favour high electrification for a given rate of flow of gas. Much the smallest bubbles are those formed chemically or electrolytically, but their use is very restricted, and not suitable for the experiments under consideration. Some form of jet must be used. By making the jet aperture about 10 μ in diameter, bubbles down to $\frac{1}{4}$ mm in diameter can be formed, but the rate of flow is restricted to 10^{-3} c.c./sec per jet. Much greater rates of flow are required to permit of the electrification being measured promptly. A flow of $\frac{1}{10}$ c.c./sec per jet can be obtained by increasing the jet aperture about five times, but the bubbles are now 1 mm in diameter. Ten such jets in a small bulb constitute the "Barboteur Villiers." The figures given refer to water; the conclusions are not much changed for other liquids.

A suitable compromise between the requirements of small bubble size and large gas flow was found by using a sintered Jena glass gas distributor. This required a pressure difference between 40 and 50 cm of mercury to force the gas through it, and produced bubbles about 3 mm in diameter at a rate of 10 c.c./sec. Steady frothing to a height of 2 cm could then be obtained by carefully adjusting the depth of the distributor below the liquid surface. This depth is critical. Union of bubbles in the froth seems as likely to produce electrification as the bursting of bubbles at the surface; on the other hand, it seems desirable to minimize their union in the liquid, since this need not involve the shattering of a thin film. The Jena gas distributor, used as described, is the best compromise in all respects so far found.

A great deal of interchange of charge between the charged and uncharged particles of different sizes present in the froth appears inevitable; one should nevertheless measure the charge before this process has gone too far. At 10 c.c./sec one expects the flow to be streamline in any apparatus of reasonable dimensions. Rough calculations show that if the connexion between the bubbler and ionization chamber is not longer than 10 cm, the loss of (even small) ions to the walls by diffusion will be trivial. If the time taken to reach the ionization chamber is less than 1 sec, recombination cannot go much further than is inevitable in the froth. Dead spaces should clearly not exceed a few cubic centimetres.

The bubbler designed in accordance with these considerations is shown in Fig. 1. The bubbles are formed at the surface of the distributor *A*, and the froth caught by the hood *B*. The dead space *C* plays no part in the bubbling. Large bubbles are sometimes formed covering the surface of the froth. These pass up the inverted funnel *D*, and burst at *E*. The resulting liquid is returned to the main body at *F*, outside the funnel. Fine spray can be shot to a height of 10 cm or more by the bursting of bubbles: such spray is directed by the funnel to the top of the chamber *G*, inter-

cepted, and returned to *F*. The gas then passes through the settling chamber *H*, the purpose of which is to prevent drops of liquid from reaching the ionization chamber. No fine particles have time to settle. So little liquid was, in fact, collected in *H*, that there was no need to arrange for its

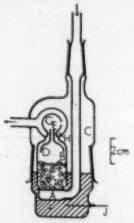

Fig. 1. Diagram of bubbler

return to *F*. The bubbler was of Pyrex. It was screened by earthed tinfoil; the earthed electrode *J* prevented any accumulation of charge in the liquid. It will be seen that this bubbler delivers all the débris from the froth, other than mother liquid, to the ionization chamber, sufficiently quickly for its character not to be very much changed. There is naturally considerable evaporation from the liquid: this results in an appreciable drop in temperature as the gas passes through the bubbler. In consequence the gas becomes unsaturated when it subsequently warms up, and there is no tendency for any liquid to be deposited.

The principle difficulty in measuring the charge comes from temperature changes, which cause movement of the ionization chamber electrodes giving capacitance changes which result in unsteadiness of the electrometer. It was calculated that a movement of a few wavelengths of light would give a marked electrometer shift, and in preliminary experiments shifts even resulted from the movement of gas displacing an insufficiently rigid electrode. The trouble was greatly reduced, though not completely eliminated, by having a plane parallel arrangement of three electrodes, so that movement of the middle collecting electrode caused opposite and nearly equal capacitance changes with respect to the two outer charged electrodes. This ionization chamber is shown in section in Fig. 2. The collecting electrode *A* consists of a circular disk attached to a tube carried by the insulator *B*. The gas enters through the earthed tube *C* which is inside *A* and at nearly the same potential. There is therefore practically no collection of ions until the gas reaches the space between *A* and the charged electrode *D*. Here ions of one sign are collected upwards; débris cannot reach the electrode connected to the electrometer by falling under gravity. The electrode *E* is at the

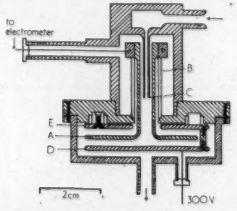

Fig. 2. Diagram of ionization chamber

same potential as *D*, and compensates for small displacements of *A*. The radii of *A*, *D* and *E* are 2 cm; the gap between them $2\frac{1}{2}$ mm. With 300 V between *A* and *D*, ions are removed down to a mobility of about 3×10^{-4} cm^2 sec^{-1} V^{-1}. A Compton electrometer was used, working at about 3000 divisions/V. By reversing the collecting voltage, ions of either sign could be collected.

Cylinder gases were used for the experiments. On passing nitrogen straight from the cylinder into the ionization chamber, a drift of 7 div/min resulted from natural ionization of the gas by cosmic rays and radioactive contamination; this effect was eliminated by interposing an additional ionization chamber calculated capable of removing ions down to a mobility of about 3×10^{-5} cm^2 sec^{-1} V^{-1}. It was noticed during these tests that, if new rubber tubes were used, large and erratic charges were indicated, presumably the result of dust charging. The sintered glass distributor filters out all dust in the bubbling experiments. The electrometer steadiness was impaired when the gas flow was first started with a liquid in the bubbler. In addition to incomplete compensation of temperature effects, a shift is to be expected from the change in dielectric constant in the collecting space. The initial unsteadiness amounted to a few tens of divisions; after the first few minutes the drift never exceeded 3 div per 5 min. This was confirmed during measurements by periodically stopping the gas flow.

It was shown by De Broglie[17] that uncharged centres similar to large ions may be formed during bubbling. This was confirmed in the present work by charging them on the way from the bubbler to the ionization chamber. The gas passed first through a tube in which an ion density of the order of 10^8 ions per c.c. was maintained by a polonium source behind a thin mica window, then through an ionization chamber calculated to remove ions down to a mobility of about 10^{-1} cm^2 sec^{-1} V^{-1}. With no liquid in the bubbler, but with the gas flowing, the electrometer drift still did not exceed the above value of 3 div per 5 min: the natural drift was not increased significantly by the polonium source in the absence of neutral centres.

An approximate value of the specific conductivity of the liquids used was determined using a centimetre cube conductivity cell with platinum electrodes, resting on an electroscope to which one electrode was connected, the other being independently supported and connected to earth, so that no current could pass through the cell without passing through the liquid.

EXPERIMENTAL RESULTS

The sensitivity of the apparatus was much greater than that used by previous workers. Charging amounting to only 10^{-4} of that given by distilled water could easily be detected, or less when the electrometer was particularly steady, at the standard bubbling rate of 10 c.c./sec. The gas normally used was nitrogen. Turpentine, which is mostly pinene, gave considerable charging by comparison with the limit of detection of 3×10^{-6} V/sec. Collecting positive ions gave $8{\cdot}1 \times 10^{-4}$ V/sec; collecting negative ions gave $4{\cdot}1 \times 10^{-4}$ V/sec. Pinene gave $+ 1{\cdot}9 \times 10^{-4}$ V/sec, and $- 1{\cdot}4 \times 10^{-4}$ V/sec. The positive excess is smaller in the purer liquid, presumably because we are approaching an inversion point, since Coehn and Mozer[13] found that continued fractionation of turpentine led to a change of sign of the charging. The conductivity of the turpentine was $4{\cdot}1 \times 10^{-12}$ mho. cm^{-1}, that of the pinene $1{\cdot}3 \times 10^{-12}$ mho. cm^{-1}, only three times less, although considerable purification is required to refine the turpentine to pinene. Fractionation has not had

much effect in reducing conductivity. The pinene showed a slightly acid reaction. It was therefore treated with dilute sodium bicarbonate, washed, dried over anhydrous sodium sulphate, and distilled, the middle 30% being accepted. The conductivity was thereby reduced to $1 \cdot 6 \times 10^{-14}$ mho. cm^{-1}, *and the charging disappeared*, being now less than 3×10^{-6} V/sec, the limit of detection, for both signs of voltage on the ionization chamber.

Di-iso-amyl decane of conductivity $2 \cdot 8 \times 10^{-13}$ mho. cm^{-1} gave noticeable charging of about 10^{-5} V/sec for both positive and negative ion collection. It was treated with cold concentrated sulphuric acid, washed, dried over calcium chloride and distilled. The conductivity was reduced to $1 \cdot 8 \times 10^{-15}$ mho. cm^{-1}, and the charging, for both signs of ion collection, reduced by at least five times to below the (rather better) limit of detection.

Five other liquids gave no charging of either sign without special purification. Their conductivities were in all cases 10^{-13} mho. cm^{-1} or less. They were hexane, octane, benzene, xylene and carbon tetrachloride. A mixture of half xylene and half carbon tetrachloride also gave no charging. In the case of xylene the result was confirmed using oxygen and hydrogen as well as nitrogen.

All the liquids investigated gave rise to neutral centres on bubbling. On passing the gas from the bubbler through the charging device positive and negative centres were formed in comparable numbers. On collecting one sign in the ionization chamber it was found that they were being generated steadily, readings being within $\pm$ 6% of the mean in the worst case, and $\pm$ 1% in the best. The neutral centres were most numerous in the case of purified decane, when a mean (positive and negative) drift of $1 \cdot 7 \times 10^{-2}$ V/sec was registered, and least numerous in the case of xylene which gave 3×10^{-4} V/sec. The neutral centres from decane, after charging, gave an effect only a few times smaller than the natural charging from distilled water. Nothing was apparent to account for the different extent to which different liquids produced neutral centres.

CONCLUSION

The most plausible explanation of the electrification produced by bubbling requires it to disappear for a non-conducting liquid. We have now seen that, using apparatus of capacitance of the order of 20 cm, and capable of detecting $3 \cdot 10^{-6}$ V/sec, the charging does recede below this limit, for a gas stream of 10 c.c./sec, if the conductivity of the liquid is less than about 10^{-13} mho. cm^{-1}. Previous workers have failed to reach such a conclusion, because their so-called non-conducting liquids have had sufficient residual conductivity to be significant for the bubbling process, which is therefore seen to be a very sensitive one. Although charged centres are not produced by bubbling gases through non-conducting liquids, similar uncharged centres are formed, in comparable numbers, and can be measured after charging them with a radioactive source.

ACKNOWLEDGEMENT

The experimental work was carried out between 1937 and 1939 in the H. H. Wills Physics Laboratory, University of Bristol, and I am indebted to Professor A. M. Tyndall for having suggested investigating problems of electrification.

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DISCUSSION

Mr. E. W. B. Gill: Dr. Harper refers, at the end of his first paragraph, to the experiments of Pomeroy and he does not understand why the nozzle used did not charge up. The nozzle would not charge up as it was not insulated.

Secondly, Dr. Harper says that "Gill and Alfrey got no charging with transformer oil." What we said was that a field produced no effect. There is always a charge due to the contact potential between the oil and the tube. We disbelieve that a surface layer can give charges when a drop breaks up because the layers are indefinitely close together and the break-up methods are too rough for so delicate a separation.

Dr. G. W. Nederbragt: The contribution of impurities to the electrification of liquids, which was mentioned by Mr. Fordham Cooper and proved decisive in Dr. Harper's bubbling experiments with hydrocarbons, is also observed when such liquids flow out of metal pipes. The electrification of benzene flowing into the air out of a steel capillary of length 25 cm and diameter 0·06 cm under a pressure head of 2·5 atm was promoted, for instance, by triethanolamineoleate and by magnesium petroleum sulphonate. With 10^{-4} weight fraction of the latter substance the current was 10^{-8} A, whereas only 10^{-9} A was found when the concentration of the additive was reduced 30 times.

By adding 10^{-4} weight fraction of magnesium petroleum sulphonate the bulk resistivity of benzene is brought down to about 10^{11} Ω cm.

Author's reply: In reply to Mr. Gill, let Pomeroy speak for himself. On p. 495 he says: "Reservoir and sprayer (see figure) were carefully insulated and connected to the electrometer but no charge was found even with continued spraying. . . ."

I had assumed that absence of an effect from an applied field in Gill and Alfrey's experiment with transformer oil was to be taken as implying no charging at zero applied field. If, indeed, there *was* charging under these conditions, it could hardly have been induced by a contact potential, when the (presumably) much larger applied potential had no effect whatsoever.

The dissipation of electrical charges generated by rollers

By J. A. MEDLEY, M.Sc., Wool Industries Research Association, Torridon, Leeds

It is shown that over a large range of roller pressures, gaseous discharge imposes an upper limit to the charge density of clean, poorly conducting wool cloth or rovings; this can be further reduced by conductors auxiliary to the rollers and designed to concentrate locally the lines of force. Dissipation by conduction back through the material to the point of contact is distinguished from discharge through surface contaminant, which behaves as a leaky dielectric in the region of contact. It is confirmed experimentally that electrification rapidly disappears as the bulk conductivity of a surface agent attains a calculable critical value in practice of the order of $10^{-9}\ \Omega^{-1}\,cm^{-1}$ or, where the material itself conducts, as a parameter K approaches unity; K may be defined for fibre assemblies as well as for homogeneous materials in terms of speed, external dimensions and a directly measurable resistance.

A formidable source of static electricity in the wool textile and other industries is the pressure of rollers on sheets or cords of material. The net charge carried away may be limited by dissipation processes, which can be divided into three main types:

(*a*) *Non-conducting materials: gaseous discharge.* The importance of this limitation was shown by previous work[1] on thin films and single fibres rubbed over platinum cylinders. The present paper deals with its dependence on the pressure of the rollers, and how it is modified by the presence and shape of other conductors in the neighbourhood, which may alter the field distribution and pick up charge by gaseous conduction.

(*b*) *Electrified materials of finite conductance.* Where contact is first broken all the lines of force tend to pass outwards from the material (Fig. 1), consequently the return

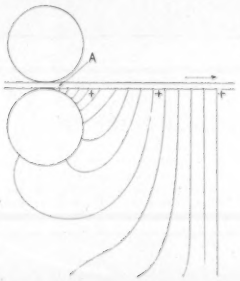

Fig. 1. Electrification of sheet material at rollers, showing direction of motion and lines of force

current is restricted in this region. The bulk conductance of the electrified material itself is unimportant unless it exceeds a certain critical value, above which electrification falls away rapidly. The critical condition for dissipation can be found in terms of the value of a parameter K, of zero dimensions in length and time, which is a function of the geometry of the system and the ratio of the conductance to the speed of rubbing. A further result of the distribution of the lines of force is the accumulation of charge at a finite distance from the point of contact determined by K, and if the material is thin compared with the radii of the rollers the return current must reach them by discharge across the gap.

(*c*) *Surface conducting agents.* By contrast, any non-electrifiable conducting agent present on the surface of a single fibre serves to bridge the gap between fibre and metal in the contact region. The dissipation is thus similar to that of a parallel plate condenser with leaky dielectric, and if charge on the electrified material remains in this region for a time comparable with the time-constant, appreciable discharge occurs. Conduction back to the point of contact is not involved, so that it is not necessary for the agent to form a continuous coating on the material in order to be effective.

These modes of dissipation are of interest in view of the rapid increase of conductance with humidity shown by most textiles, and the common practice of applying "anti-static" dressings; further work has accordingly been done as follows.

EXPERIMENTAL

(*a*) *Surface-clean materials.* The essential nature of these experiments is illustrated in Fig. 2 which shows, diagrammatically, material such as a roving (loosely twisted wool yarn) issuing continuously from a pair of rollers R. It subsequently passes near other conductors, e.g. a thin loop of wire L, a flat plate of metal A; to which some of the electrostatic charge may be lost by gaseous discharge. R, L and A are connected

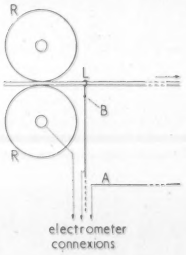

Fig. 2. Arrangement of rollers and auxiliary conductors

to an electrometer, first separately, then all together, and the charge transferred to each, corresponding to the passage of a given amount of material, is thus measured. This can be done at different roller pressures, which control the initial electrification. The final charge on the material is of course equal and opposite to that on all the conductors together. As the process is continuous, the induced charges on the conductors are constant once steady conditions have been established, so that what is measured is charge transfer. Each of the conductors was insulated and effectively at earth potential; with an appropriate known capacity to earth, small voltage changes were measured with a Lindemann electrometer. In certain cases, however, the current flowing

on to a conductor was large enough to be observed by earthing through a galvanometer.

The roller assembly was typical of drafting rollers used in worsted processing. They were 8 cm wide, mounted on ebonite and driven with a perspex bush. A continuously variable speed drive was available for much of the work. The lower driving roller, 3 cm in diameter, was of polished steel; the interchangeable upper roller was either identical with the lower, or of 5 cm diameter and faced with cork.

The lower roller only was driven. The top roller, turned by friction with the material, was spring loaded, one complete turn of the retaining wing nuts increasing the pressure by 28 kg weight. The compression of the springs was, however, large compared with the compression of the material, although small loads are subject to some uncertainty; consequently, in plotting the results, the position of zero load is only accurate to 7 kg.

The following auxiliary conductors were available (see Fig. 2):

Cylinder *B*, a straight 18 s.w.g. wire 20 mm from the point of contact and 5 mm below the issuing material.

Plate *A*, parallel to the issuing material, 5 cm below it, and extending 25 cm in the direction of motion of the material.

Loop *L*, 4 mm in diameter of 36 s.w.g. stainless steel wire, mounted at the end of 18 s.w.g. copper wire, 20 mm from the point of contact.

These conductors were not all present at once; those used in any given experimental arrangement will be denoted in this account by the appropriate letters; thus to illustrate the notation the system *R* consists of rollers only; the system *RAB* consists of rollers, the thin cylinder *B* arranged across the issuing material a little distance beyond contact, and the flat plate *A*.

Materials used were:

Roving, 1·3 g/m, average fibre diameter 20 μ.

Woollen taffeta cloth, 0·026 g/cm^2, a rough flannel-like material which, compared with nylon film, required very heavy surface loading to electrify when rubbed on a single platinum cylinder.

Whatman No. 4 filter paper (60 cm strips). This material, unlike the others, electrified negatively.

Except where otherwise stated, rovings were guided to a track in the middle of the rollers. This slightly reduced the electrification maxima as observed with cork rollers, primarily on account of the electrification of the cork. Otherwise no significant difference between the behaviour of the two types of roller has been observed.

In order to reduce the conductivity of the materials used, the experiments were performed in a room controlled at 24° C and 40% R.H. The materials were initially dried and allowed to come to equilibrium with the atmosphere. Consistent results in these and the following experiments depended on careful cleaning of the specimens. Successive soakings in alcohol and Lissapol N solution, followed by prolonged rinsing in running water and finally in distilled water were found adequate.

(*b*) *Conducting materials.* The conductance of woollen materials was varied by varying the relative humidity, and also their salt content.[2] Potassium chloride was introduced by soaking in solutions of different concentrations, an N/3 solution giving the highest conductivity required. Surplus liquid was removed by rubber rollers. Uniform treatment and drying were found essential and conductance also depended on the method of conditioning on account of the sorbtion hysteresis of wool. It was necessary to measure the conductance of unit length of the roving to an accuracy of ±20% immediately before and after electrification; conductance of unit length per unit width of the strip was similarly measured. This was done by the condenser-leak method employing a Lindemann electrometer. Lengths tested were short compared with the average lengths of the individual fibres. Moisture meter electrodes were used for rovings of low conductance, and the appropriate conversion factor determined.

(*c*) *Applications of surface agents to rovings.* Solutions of Aerosol OT in a standard wool combing oil were found suitable since conductivities measured in bulk between platinum electrodes after oven drying were found consistent with those of 10 μ films spread on Alkathene, measured at 40% R.H. Conductivity varied almost linearly with concentration of anti-static agent, and was, therefore, easily controlled. The maximum concentration used was 10%. Dielectric constants at 1000 c/s were of the order of 3.

Roving in lengths of 2 m was dressed with 3% of the oil solutions of anti-static agents which were added in 10 c.c. of petrol ether as uniformly as possible. Length-conductance measurements indicated tolerably even distributions, but unless the fibres were very carefully cleaned, small amounts of impurity (in particular, residual Lissapol) gave spurious anti-static effects. The agent was also applied to the rollers in petrol ether, to obtain the best possible spreading.

Where the oil solution was applied to the wool, the rollers were initially dry, and became coated with oil during the passage of the wool. In order to establish steady conditions as rapidly as possible rovings were guided to a single track at the centre of the rollers. The electrification then fell to a steady value during the passage of the first 20 cm of roving. Where the oil solution was applied to the rollers and not to the rovings, the latter wandered across the entire roller width; in this way the thickness of the oil film was not seriously reduced by the passage of the wool.

SUMMARY OF RESULTS

Figs. 3 and 4 show the charge transfer between the electrified material (cloth or roving) and the conductors (parallel-plane and bar) for a range of roller pressures. The material acquires a positive charge, some of which is transferred to the other conductors. The net charge finally carried away by the

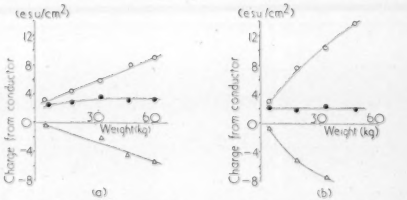

Fig. 3. Charge transfer per unit area of electrified woollen taffeta using steel rollers. Surface density of cloth, travelling at 10 cm/sec, is 0·026 g/cm^2

(*a*) System *RA*
- ○ *R* Rollers
- △ *A* Plane parallel metallic sheet
- • *RA* Both conductors (= charge on cloth)

(*b*) System *RAB*
- ○ *R* Rollers
- △ *B* Bar 1·6 mm diameter
- • *RBA* Both conductors (= charge on cloth)
- *A* Plane parallel metallic sheet is negligibly electrified

material is equal to the algebraic sum of the charges *leaving* the rollers and adjacent conductors. It is noticeable that the bar *B* dissipates charge more readily than the parallel plane *A*.

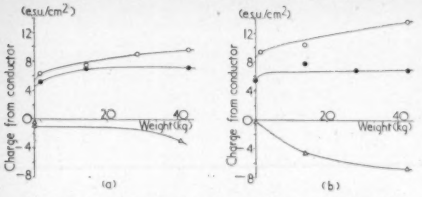

Fig. 4. Charge transfer per unit area of electrified roving using cork rollers. Linear density of roving, diameter taken as 0·4 cm, travelling at 10 cm/sec, is 1·3 g/m

(*a*) System *RA*
- ○ *R* Rollers
- △ *A* Plane parallel metallic sheet
- ● *RA* Both conductors (= charge on roving)

(*b*) System *RAB*
- ○ *R* Rollers
- △ *B* Bar 1·6 mm diameter
- ● *RBA* Both conductors (= charge on roving)
- *A* Plane parallel metallic sheet is negligibly electrified

Similar results were obtained when the rovings were passed through the wire loop *L* except that the rovings were practically discharged by the loop; they acquired less than 0·2 e.s.u./cm², for all loads, the charging of *R* and *A* resembling that for the *RAB* system with the charge on *L* equal and opposite to that on *R*. There was, of course, contact between roving and loop, but this was extremely light compared with that produced by rollers. Electrification was found to be independent of roller speed.

Fig. 5 shows a typical relation for electrification over a wide range of conductance, and shows how the charge falls

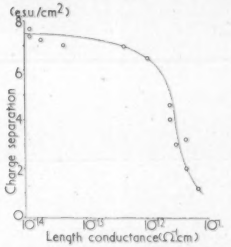

Fig. 5. Electrification-conductance relation for wool roving emerging from rollers at 15 cm/sec

rapidly when conductance increased beyond a critical value. A series of conditions of speed and conductivity under which electrification was reduced to half is given in Table 1.

Fig. 6 shows a relation in which the material did not con-

Table 1. *Conduction in electrified material; critical conditions*

RA systems. Charge transfer from rollers halved by conduction

Material	Rollers	R.H.	Conductance k', k'' e.s.u.	Speed v cm/sec	K from equations (4) and (5)	Remarks
Woollen taffeta, 5 cm strip	Steel	40	1·1	5·0	0·22	KCl treated
		75	0·33	2·0	0·17	
		75	1·4	11·0	0·13	
Filter paper, Whatman No. 4	Steel	40	1·5	11·0	0·14	
Roving 1·3 g/m, 0·4 cm diameter	Cork	40	3·0	15·0	0·16	KCl treated. See also Fig. 5
		70	3·2	11·0	0·23	
		70	0·50	1·25	0·32	

Table 2. *Surface conducting agents*

Charge density on rovings reduced to 3·5 e.s.u./cm². Load 30 kg

Composition of agent	Bulk conductivity $1/\rho$ ohm^{-1} cm^{-1}	Rollers	Application	Mean thickness 1 μ	Speed v cm/sec	Calculated $4\pi/\varepsilon\rho_v\sqrt{(2rl)}$
Combing oil only	2×10^{-12}	Cork	Large excess on rovings and rollers	—	—	Large charge reductions unobtainable
1% solution Aerosol OT in combing oil	1×10^{-10}	Cork	3% on wool	0·15	3	0·85
3% solution Aerosol OT in combing oil	$2{\cdot}5 \times 10^{-10}$	Cork	3% on wool	0·15	10*	0·6
4% solution Aerosol OT in combing oil	3×10^{-10}	Steel	0·04 g applied to rollers	2·0	10	2·7
10% solution Aerosol OT in combing oil	6×10^{-10}	Steel	0·01 g applied to rollers	0·5	10	2·7

* See Fig. 6.

duct, but a surface conducting agent was present on the wool; it is similar in form to that of Fig. 5. The critical bulk conductivities of such agents are given in Table 2.

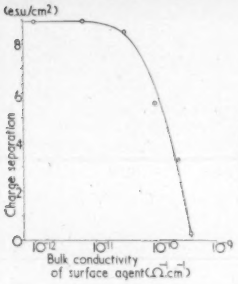

Fig. 6. Electrification of a roving in the presence of surface conducting agents. 3% oil solutions of Aerosol OT on wool. Speed 10 sec/cm

NON-CONDUCTING MATERIALS (GASEOUS DISCHARGE)

The surface density of electrostatic charge on a body is directly related to the potential gradient surrounding it, and so is limited by the dielectric strength of the medium. The order of magnitude of charge densities arising from separating a double layer, to which frictional electrification is often attributed, would be 10^4 e.s.u./cm^2 for a contact potential of $\frac{1}{3}$ V across a double layer 1 Å thick, compared with a theoretical maximum of 10 e.s.u./cm^2 on a plain surface in air at atmospheric pressure. It is also known that several hundred e.s.u./cm^2 may be generated on some polymers by mercury. Allowing for the relatively small total true area of contact in a frictional process, there is a high probability that in many instances frictional electrification will be discharge-limited.

Thin single fibres can be electrified to an average of 50 e.s.u./cm^2 of circumference and retain this charge in the atmosphere. A collection of such intensely electrified fibres could not be present in a roving, however, because the field at the external circumference of the roving would greatly exceed the dielectric strength of the atmosphere. The maximum charge on a roving, therefore, depends on its external dimensions and is best expressed as the equivalent charge density on its enveloping surface. The theoretical maximum for a cylinder of 4 mm diameter is 20 e.s.u./cm^2. For a plain sheet it is either 10 or 20 e.s.u./cm^2, depending on whether the lines of force emerge from one or both surfaces; in practice these figures appear to be more than halved by uneven charging. For plain sheets (Fig. 3) the charge density attained 9 e.s.u./cm^2 on leaving the rollers, where lines of force were short and emerged from both surfaces, but was reduced to 3 e.s.u./cm^2 after passing parallel to the plain sheet of metal. Similarly the rovings which emerged from the rollers as plain sheets of slightly reduced surface area, acquired a maximum of 7 e.s.u./cm^2 (Fig. 4).

The data in Figs. 3 and 4 may be summarized as follows. Increasing the pressure on the rollers increases the area of contact with the wool and therefore the charge separated. As suggested in the introduction the final charge on the material is determined by gaseous discharge back to the rollers at the point at which the field is most concentrated and also to adjacent conductors. Moreover, these conductors modify the electric field, accepting lines of force in preference to the rollers, thus reducing discharge back to rollers, i.e. increasing the net charge separation from them.

A conductor whose surface is small compared with the area of material under its influence causes a large local concentration of field and considerable discharge. Excess loading merely causes more charge to be transferred from the rollers to the conductor *via* the wool. A useful application of the discharge of a sheet by a thin bar is to hang an earthed chain across moving electrified cloth; this method of eliminating static troubles depends not on contact but on gaseous discharge. The virtually complete discharge resulting when a roving passes through a loop of thin wire does not seem to be applicable to one of the more important static problems in the wool textile industry, which is the attraction and retention of short fibres by the rollers.

ELECTRIFIED MATERIALS OF FINITE CONDUCTANCE

A non-homogeneous, electrified material of mean conductivity k moving at speed v transfers charge at a net rate I which is the sum of a conduction term and a velocity term. Taking σ as the charge density and E as the corresponding field responsible for conduction one may write

$$I_1 = v\sigma + ykE \tag{1}$$

for a sheet of thickness y, and

$$I_2 = 2\pi\sigma av + \pi a^2 kE \tag{2}$$

for a roving or other cylindrical specimen of radius a. These reduce to the form

$$I = v(\sigma + KE) \tag{3}$$

where K is defined by

$$K = y(k/v) = k'/v \tag{4}$$

for a sheet of conductance k' for unit length and breadth, and

$$K = (ak/2v) = k''/2\pi av \tag{5}$$

for a roving of length-conductance k''. K can thus be determined from experimental data, and is independent of the compression caused by the rollers, provided the surface area of the material is unaltered. This is approximately true in practice; a cylindrical roving is in effect transformed into a sheet having the same value of K.

To derive the precise K-value corresponding to a given degree of dissipation requires a series of laborious computations of σ and E at all points on the material, but a rough estimate can be made as follows. Consider a case in which the charge density at a point A, a short distance from the rollers, is limited by gaseous discharge to a value σ_A, independent of conductance. The corresponding dissipating field E_A will approximate to $4\pi\sigma_A \cos\theta_A$, where θ is the angle of inclination of the lines of force to the direction of motion: A will have some value in excess of 90° (see Fig. 1), governed by the tendency of the lines of force to be normal to the cylinder. Then from equation (3)

$$I_A = v\sigma_A(1 + 4\pi K \cos\theta)$$

For zero dissipation

$$I_A = v\sigma_A$$

and hence for 50% dissipation, a critical condition,

$$K_{crit} = -1/8\pi \cos\theta_A \tag{6}$$

If θ_A lies somewhere between 95° and 120°, K_{crit} must be between 0·4 and 0·1. The experimental values in Table 1, as well as those previously obtained for rubbing on single cylinders, are in tolerable agreement with this estimate, since the practical range of K covers many powers of ten.

SURFACE CONDUCTING AGENTS

The length conductances of oiled rovings, measured both directly and using moisture meter electrodes, are low, and the K-values calculated as above are less than 0·01 when there is almost complete dissipation. Even if uniformly distributed on the fibres, the small amount of agent applied could not provide sufficient lengthwise conductance for dissipation, particularly when applied to rollers and not to rovings. This points to a close connexion between the bulk conductivity of applied surface agents and the electrification, but shows that the mechanism is not the one discussed in the previous section. On the alternative hypothesis that the agent acts as a leaky dielectric for a short interval of time t after fibre-to-metal contact is broken, the following condition would hold for an appreciable fraction of the number of contacts if charge separation is to be observed, ϵ and ρ being the dielectric constant and resistivity of the agent:

$$t < (\epsilon/4\pi)\rho n \qquad (7)$$

where the charge is reduced by a factor exp (n) (e.g. 100-fold for $n = 4{\cdot}6$, approximately halved for $n = 1$).

The data in Fig. 5 and Table 2 are in accord with the view that, since most of the contacts must be broken near the position of minimum clearance between the rollers, t is governed by tangential movement of the fibres from them. For then

$$v^2t^2/2r = l \qquad (8)$$

where v is the speed of the roving, r the radius of the rollers, and l the thickness of the intervening conducting agent. Thus

$$(4\pi/\epsilon v\rho)\sqrt{(2rl)} < n \qquad (9)$$

would be the critical condition for electrification, n being a number of the order of unity; this condition is adequately confirmed by the experimental work if surface tension effects cause l to be somewhat greater than the thickness of agent when distributed uniformly over the rollers or the 20 μ wool fibres. (Length-conductance measurements on the rovings treated with 3% agent from petrol ether confirmed that it was evenly distributed. No allowance has been made for agent transferred from fibres to rollers. The results for oiled rovings in Table 2 are thus based on low estimates of l, and therefore give low n.)

The practical behaviour of many anti-static agents is found to conform to the above pattern; a bulk conductivity of between 10^{-9} and 10^{-10} is a useful criterion for the effectiveness of a 3% oil application to the material. Some agents (e.g. Lissapol N) are used in lower amounts but provide higher conductivity. The fact that even smooth steel rollers retain their anti-static properties during the passage of several metres of roving, which removes the 1 μ film of conducting agent only slowly, shows that "anti-static rollers" have economic advantages. On the other hand, a material once treated remains anti-static for a number of operations.

ACKNOWLEDGEMENTS

I am indebted to the Director and Council of the Wool Industries Research Association for permission to publish this paper, to Mr. G. King for discussion, and to Mr. D. Eames for assistance with the experimental work.

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DISCUSSION

Mr. J. A. Wells: Mr. Medley had not stated whether the steel rollers described in his paper were connected to earth or insulated from earth.

In a continuous friction process in which the mean inter-surface capacity is constant the charge carried away on the rovings will be largely dependent on the facilities for electron transfer between the rollers and earth. If the rollers are insulated it is likely that the charge on the wool rovings will be considerably reduced.

In some experiments with numerous samples of aircraft camera film it was found that if a cork friction pad over which the film was passed, when winding between two spools, were insulated from earth the mean charge on the film surface leaving the pad was zero. For electrostatic purposes the cork may be considered conducting. However, in the case of film, a similar result is obtained if the pad is replaced by an insulated metal plate, or an insulating plate, such as a perspex plate.

The mechanism of this process may be considered as follows. When the film starts to move the plate will collect electrons (or give them up in the case of other dielectrics) and it becomes negatively charged. The rate at which the plate is charged, however, falls off progressively because any charge on the plate opposes the forces causing electron separation. Finally, a state of equilibrium is reached where the charge on the plate is a maximum and is sufficient to suppress any further electron transfer from the film. This occurs after one or two feet of film have passed over the plate, depending on its capacity, and thereafter the mean charge on the film leaving the plate is zero.

No high degree of insulation of the plate supports is necessary and it would appear that for aircraft camera film, if the total leakage resistance is $10^{12}\ \Omega$ or more, the charge on the film is negligible. If the plate insulation resistance is reduced to $5 \times 10^{11}\ \Omega$ the charge on the film is only 10% of the value given with the plate earthed.

An effect related to the foregoing has been described by Gill and Alfrey*; in their case frictional charges were eliminated by applying an external electric field to the frictional surfaces, one of which was an earthed conductor.

Author's reply: The rollers are in effect earthed; the charges transferred to them and a parallel capacity to earth are measured, as explained in the paper, by the corresponding changes in potential, which are very small.

If the rollers had been insulated, and the process had been carried on for a sufficiently long time, there would have been a tendency for the rate of charging to be reduced, as Mr. Wells says. However, the phenomenon probably results, not from interference with the initial electrification process, whether this be electron transfer or not, but from an increase in the subsequent discharge, in this case gaseous discharge. I have discussed this point with reference to Gill and Alfrey's work in another paper presented to this conference (see p. S 28).

Insulation of textile machinery is not a suitable remedy for three reasons, the residual attraction between the material and the machinery remains; it is a matter of great practical difficulty to maintain the insulation, and the capacities involved are often dangerously high.

* GILL, E. W. B., and ALFREY, G. F. *Nature* [*London*], **163** (1949).

The electrostatic charging of some polymers by mercury

By J. A. MEDLEY, M.Sc., Wool Industries Research Association, Torridon, Leeds

A method is described by which very heavy charge densities may be measured after separation. The influence of externally applied fields on the apparent electrification is described, and also the electrostatic contribution to hysteresis of contact angle.

According to Helmholtz, electrical charging by separation, without rubbing, is due to breaking contact at a double layer and is sufficient to account for frictional electrification. Harper[1] has recently shown that, for metals, true separation charging does occur and is equivalent to the separation of a double layer, about 25 Å in thickness, charged to a potential difference equal to the difference in the work functions of the two metals. For a potential difference of 1 V, the corresponding charge separation per unit area of double layer would be 1000 e.s.u. This is much less than the charge densities usually encountered in unseparated double layers, being reduced by electron tunnelling when contact between the metals is first broken; nevertheless it corresponds to an external field of more than 10^6 V/cm. If similar charge separation occurred with non-metals it would probably be large enough to explain the magnitude of triboelectric effects, even allowing for the fact that in such cases the total true area of contact is only a small fraction of the apparent area of contact.

Separation charging without inter-solid rubbing may conveniently be obtained by mercury against dielectrics, and a technique has been adopted which allows very heavy charge densities to be measured. The opportunity has been taken to investigate and describe the relations between the electrification and an externally applied field, as well as the contributions made by electrostatic forces to the hysteresis of contact angle between solid and liquid.

APPARATUS

In order to reduce to a minimum the dissipation of static charge following the withdrawal of mercury from the solid, the electrification was carried out in a vacuum; further, the electrified material was in the form of a thin film, one side of which was kept permanently near earth potential by contact with mercury and the other side charged by bringing more mercury into contact and then withdrawing it again. The effect of such an arrangement may be seen in Fig. 1.

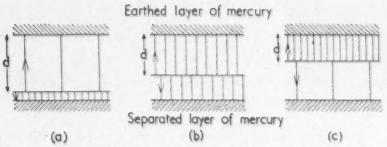

Fig. 1. Reduction in field between separated surfaces by use of a thin film, thickness d, dielectric constant k

(a) Separation small compared with d/k.
(b) Separation d/k.
(c) Separation large compared with d/k.

The field set up between the charged solid surface and that of the receding mercury begins to fall rapidly when the distance of separation becomes comparable with d/k, the thickness of the film divided by the dielectric constant.

The apparatus is shown in Fig. 2. The film F sealed the bottom end of a vertical glass tube and supported a layer of mercury electrically connected *via* the vacuum seal S to the needle of a Lindemann electrometer with appropriate capacity to earth. The lower surface of the film just cleared the end of a vertical U-tube containing more mercury to be brought into contact, which was made and broken by rotating the

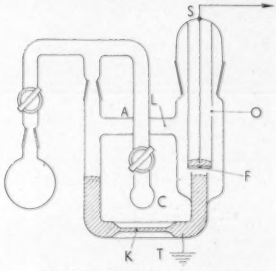

Fig. 2. Electrification apparatus

whole apparatus around C, a ground glass joint with horizontal axis and communicating with a diffusion pump. The mercury in the U-tube was earthed *via* a tungsten seal T. R is a reservoir enabling water vapour to be admitted to the system. The limb L and the orifice O equalize the pressure throughout the apparatus, and there is a clamp at A to provide rigidity. The contact between mercury and polymer was clearly visible, so that rough estimates of contact angles could be made.

MAGNITUDE OF CHARGE SEPARATION; ULTIMATE LIMITATIONS TO SEPARATION

It was found that the density of charge obtained on a given film was increased if the surfaces were fresh. The solid surface was heated or flamed immediately before insertion in the apparatus; the mercury was redistilled, and flowed through the capilliary K shown in Fig. 2. Charge densities were lower in air than in a vacuum, and at intermediate pressures lower still. But even in a vacuum there was a maximum to the electrification obtainable, which was controlled by the finite capacity per unit area of the film. This is shown by Fig. 3 from which it is clear that the initial charge separation may be in excess of 500 e.s.u./cm^2. The object of using the film is to provide a large capacity to absorb the induction due to the separated charge, and so reduce the field between the surfaces to a minimum; accordingly, the higher the capacity the larger the maximum charge density, which then appears to be determined by short range dissipation. The fields across the interface in the initial stages of separation must be at least 2×10^6 V/cm, and these are likely to cause considerable field emission.[2]

With nylon, mica and Alkathene films in a vacuum, the maximum electrification was independent of time of contact, and also speed of movement of the mercury within the rather

narrow range within which this could be varied. The charge on the film surface was quite stable, and on making contact a second time the electrometer returned to its original reading. The charge generated on the glass of the U-tube produced a negligible error in these cases.

The maximum charge that could be produced on horn keratin film was much smaller (less than 5 e.s.u./cm^2) and

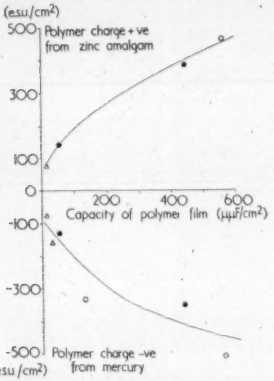

Fig. 3. Increase of observed charge separation by use of thin films

filter paper also electrified only feebly (7 e.s.u./cm^2). On the other hand Cellophane and horn keratin glazed by steaming between glass plates under pressure, charged strongly, substantially in accordance with Fig. 3. The fibrous structure of the surfaces of the original keratin and filter paper probably limits contact to a small fraction of the apparent area. This is supported by the fact that the capacities of such films measured between mercury are lower when measured between mercury alone than when the surfaces have been coated with colloidal graphite.

The maximum charge for a given film capacity remained the same after a small quantity of sodium, zinc, lead or tin was added to the mercury, although the sign of charge on nylon, Alkathene and mica was reversed from negative to positive. This reversal, depending on the electropositive character of the added metal, was previously found by Coehn and Curs[3] working on such materials as quartz, ebonite and carborundum. Their observations that less than 0·1% additions of foreign metals are usually required for reversal, and that there is little or no distinction between the behaviour of different dielectrics, were confirmed. Attempts to determine critical amalgam concentrations which gave charge densities intermediate between the positive and negative extremes were unsuccessful; a period of erratic electrometer deflexions, which quickly reverted to the maximum reading one way or the other, was all that could be obtained. This difficulty in balancing or even reducing the electrification by slight alterations in the character of the metal again suggests that the initial charge separation is still greater than that which can be observed.

It seems then that the separation of mercury from the surface of a dielectric causes a charge well in excess of 500 e.s.u./cm^2 over the apparent area of contact, i.e. at least comparable with Harper's results for inter-metallic charge separation and should be sufficient to account for tribo-electric effects. The charging of nylon and Alkathene fibres by rubbing over platinum cylinders has been investigated previously[4] and the maximum charge densities obtainable over the apparent area of contact found to be much smaller, since with a normal force per unit apparent area of contact of 10^4 dyn/cm^2, the corresponding electrification was approximately 1 e.s.u./cm^2, and roughly proportional to the normal force. Limitation by gaseous discharge began to make itself apparent when the charge density exceeded 3 e.s.u./cm^2. Again, the maximum charge density obtainable by rubbing a 20 μ diameter nylon fibre against platinum was 50 e.s.u./cm^2; this required heavy loading and continuous rubbing. It is difficult to form an estimate of the true areas of contact in these cases but it should be remembered that the polymer passes continuously over the metal, so that each polymer asperity has a good chance of being electrified.

EFFECT OF APPLIED FIELDS

It has been suggested[5] that information about the mechanism of electrification may be provided by studying the effects of externally applied fields. The present experimental arrangements could be conveniently adapted to investigate this; the films in a vacuum were good insulators, and the arrangement shown in Fig. 4 was adopted. Whilst

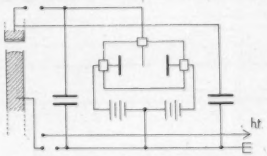

Fig. 4. Electrometer connexions

the mercury in the U-tube was in contact with the film it was connected to the output of a d.c. power pack giving up to 1500 V, and during this time the electrometer was isolated. After the mercury had receded from the surface, it was earthed, and the electrometer connexion to the upper surface of the film was remade. The zero reading was first obtained with all surfaces uncharged; it was found that all subsequent readings were determined by the value of the h.t. during the previous contact operation, and was reproducible on nylon, Alkathene, mica and keratin.

If the applied voltage between the two portions of mercury in contact with opposite sides of the film is V, and the capacity is C per cm^2, then there is a net charge VC on either side of the condenser so formed. If this is able to pass from metal to dielectric, the electrical field across the interface (e.g. any field due to a contact potential) will not depend on the applied external potential. The net charge on separation will thus be the normal charge obtained in the absence of the applied potential, plus VC, and this difference will be maintained at all stages of separation, independent of any short range dissipation, because at no stage does the external potential influence the net field between the separating surfaces. In Fig. 5 the electrification has been plotted against V in a typical case, and the result is a straight line of slope C. Sufficient external field has been applied to reverse the sign of the original electrification.

Thus one concludes that the application of an external

potential gives no information about the intrinsic mechanism of electrification beyond confirming that charge may transfer freely across the interface. It may be pointed out that the external field will also affect the charge transfer to and from a material which conducts, but that in the present form of

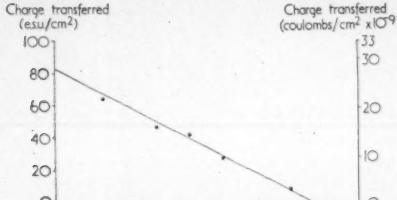

Fig. 5. Effect of applied field on the electrification of a nylon film. Measured d.c. capacity 64 $\mu\mu$F/cm^2. Slope 72 $\mu\mu$F/cm^2

apparatus a continuous current would flow, making measurements valueless. But if the upper surface of the film were electrically isolated, the additional charge due to an external field would appear on this upper surface, and the intrinsic electrification would be the same as if no external field were applied. This effect may be demonstrated by sliding a partially conducting powder (e.g. keratin at high moisture content) down an inclined plane beneath a high potential electrode.

CONTACT ANGLE AND ELECTRIFICATION

The relation

$$W = (1 + \cos\theta)\gamma$$

gives the work of adhesion of a solid-liquid interface in terms of the surface tension γ of the liquid and the contact angle θ. When a liquid recedes from a surface which has become charged by the contact, additional work is done against the electrical forces, so that the receding contact angle is diminished as compared with the advancing contact angle. It is of some interest to know whether this contribution to the well known hysteresis may be appreciable; Yarnold[6,7] has suggested that it may explain the behaviour of mercury in glass capillaries. Now a 5 μ mica film, of measured capacity 500 e.s.u./cm^2, is left with a measured charge of 500 e.s.u./cm^2 after contact with mercury. The corresponding energy is 250 ergs/cm^2, which is comparable with the surface tension, hence in this case there must be a considerable reduction in θ. The reduction would be greater still if, on account of dissipation, 500 e.s.u./cm^2 did not represent all the charge originally separated, and also if one side of the mica were not earthed, since this earthing serves to eliminate the interaction between the surfaces when separated to distances comparable with the film thickness.

The observed contact angles were consistent with the above theory. The contact angle of mercury advancing over an uncharged surface of mica was of the order of 135°, but only 90° receding. It was also about 90° advancing over a heavily charged surface. Thin films of nylon, Alkathene and cellulose acetate behaved similarly in these respects. By contrast rough keratin films and filter paper, which electrified only slightly, showed advancing and receding contact angles that were in every case 180° or nearly so which, as Cassie and Baxter have shown,[8] is consistent with the assumption that the true area of contact is small. Wenzel's explanation of large contact angles on rough surfaces assumes that the true area of contact is greater than the apparent area.[9] Smooth keratin and cellulose films, however, behaved similarly to the other polymers, with much smaller contact angles and pronounced hysteresis. This may account for the observations of Rosenberg,[10] and de Turk and Lockenwitz,[11] that mercury sticks much less in roughened glass capillaries than in smooth ones.

It is possible that electrical hysteresis may also occur in cases where dissipation is too rapid for large charges to be observed, and account for some at least of the contact angle phenomena of water with solids on the assumption that there is large initial charge separation over short distances.

ACKNOWLEDGEMENTS

I am indebted to the Director and Council of the Wool Industries Research Association for permission to publish this paper. The apparatus was made by Mr. F. Bond.

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The role of asymmetric rubbing in the generation of static electricity

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Two independent types of contact electrification are discussed; the one requiring different surfaces, but not needing friction; the other requiring *asymmetric* rubbing, but not a difference in the surfaces. It is suggested that the combination of these two effects which occurs when different surfaces are rubbed together (usually asymmetrically) is a contributory factor to the notorious uncertainty of such experiments. It is shown that almost all rubbing processes involve local asymmetry, with the result that like surfaces rubbed together, though each neutral as a whole, are covered with a pattern of opposite charges. A similar effect accounts for the different triboelectric behaviour of surfaces of the same material but different degrees of roughness, and occurs as a complication in the rubbing together of different materials. The part played by asymmetric rubbing between two solids in observed transference of charges to the air is discussed.

Experiments are described in which all possible pairs of ten different materials are brought into contact by a method involving the minimum of rubbing. It is shown that the results, with very minor exceptions, are in accordance with the existence of a self-consistent electrostatic series.

The separation of charge by the asymmetric rubbing of like surfaces is discussed, and the hypothesis suggested that it is due to the thermal *gradient* across the interface, and that it is analogous to thermal diffusion and to the Thompson thermoelectric effect in metals. As yet little experimental evidence exists to test this hypothesis, but suggestions are made as to how it might be obtained.

Those who have experimented with charges produced by the rubbing together of different surfaces agree that a most striking feature is their apparently capricious nature. One day they appear to be formed in accordance with some rule, such as that of an "electrostatic series"; the next day, or in another place, they obey no such rule. Their signs appear to change with circumstances as readily as their magnitude. In the textile process known as warping, in which yarns from a large number of bobbins are brought together to form a warp for weaving cloth, it is a common, but not invariable, occurrence for the charge on acetate rayon yarns running through glass guides to reverse when the speed of motion is increased. Warps of acetate rayon that are being woven on two neighbouring looms, apparently identical in all respects, will both be strongly charged, but with opposite signs. This uncertainty of behaviour has often been put down to contamination or strain of the surfaces, and in the textile mill this is likely enough (though it could hardly account for the effect of speed mentioned above). It is certainly true that very thin films can greatly affect potential differences across interfaces. The author has never felt, however, that this by itself was a satisfactory explanation of the unpredictable behaviour of static in laboratory experiments and has rather believed, with others[1, 2, 17] that the observed charges must have resulted from the superposition of two or more quite different mechanisms which were differently affected by the circumstances, and might assist or cancel out each other according to the conditions.

These ideas can be given more precision by considering the following two experimental facts, of which the first is well known, and the second, though it has been described by Shaw,[3] has received little attention.

(i) *Separation of charge occurs between two different surfaces which are brought together and separated without overt friction.* If the circumstances are such that the real area of contact is an appreciable fraction of the total surface area, large charges may be produced in this way, often limited only by discharge in air as the surfaces are separated.

(ii) *Separation of charge occurs between two identical surfaces which are rubbed together in an asymmetric manner so that the friction occurs mainly at one spot on one of the surfaces, but is spread over a large area of the other.* The signs of the charges are reversed if the roles of the two surfaces are interchanged, showing that the charges are not due to a difference in contamination of the surfaces.

These phenomena are suggestive, the one of an *equilibrium* effect akin to the contact potential of metals, requiring a difference between the natures of the surfaces but not needing friction (Helmholtz's hypothesis, in fact); the other of a *kinetic* process not needing different surfaces but depending upon asymmetric rubbing. It must be admitted that neither interpretation can be regarded as "water-tight" without further evidence. It could be argued, for instance, that it is impossible to bring two surfaces together and separate them without some friction, or that the separation of charge in the first phenomenon does not take place when contact occurs but is brought about by a kinetic process during the separation of the surfaces. Conversely, it could be suggested that the second phenomenon was really an equilibrium process depending upon the rubbing away of a surface film from the body which is rubbed all at one spot, but not from the other body, thus creating the necessary difference in the surfaces. Shaw[3] believed that it was due to a difference in the state of strain of the two surfaces, produced by the rubbing process. The author prefers, however, the interpretations first given and some evidence bearing on this question is presented later in this paper, together with a hypothesis as to the nature of the second phenomenon. Though it will be convenient to refer to the phenomena as the "equilibrium" and "kinetic" effects respectively, inverted commas will be used in this paper when employing this terminology, in deference to the disputable nature of the author's interpretation of the facts.

Before discussing the nature of the two phenomena further, let us consider some consequences of the experimental fact that they both exist.

Some consequences of the observed facts

(1) When two ordinary solid surfaces (i.e. not accurately flat or exceptionally clean) are brought together under moderate pressure the actual area of contact is a small fraction of the total area. If now two such surfaces of identical material are rubbed together in an apparently symmetrical fashion, it will happen that high spots on the one will be rubbed asymmetrically on the other, and *vice versa*. In view of the "kinetic" phenomenon described above it seems that the two surfaces, though nearly neutral in overall charge, should each have spots of one charge and streaks of the other, and be far from neutral when examined locally. Hull[4] has observed, and described without comment, something like this on paper coming from the printing press. He

used, in order to show up the patches of different charges, a mixture of coloured powders first suggested by Bürker.[5] The present author has carried out some experiments to look for this effect, using a similar mixture of powders. Fig. 1 shows the result of rubbing two pieces of polythene sheet together. The dark spots were positively charged, and the

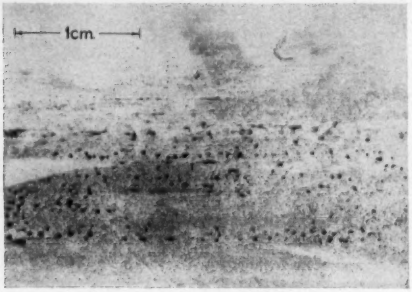

Fig. 1. Distribution of opposite charges on polythene sheet rubbed on another piece of the same material.

grey areas negatively, whilst the light areas did not collect any powder and presumably carried little charge of either sign. It will be seen that the phenomenon is very much as anticipated. Irregular patches of opposite charges were found on other materials, such as Perspex and ebonite, but the slightly uneven surface of polythene sheet makes it ideal for demonstrating this effect. Some of the larger patches on Perspex and ebonite were also detected by exploring the surface of the rubbed materials with a small probe, shielded except at its extreme tip, and connected to a Baldwin–Farmer electrometer. The probe was moved slowly over the surface at a distance of a millimetre or so, and the area which affected it at any one position was a circle of several millimetres diameter, so that it was not suitable for detecting very fine structure in the surface charge.

(2) If two insulating surfaces are rubbed together, which consist of the same material but of which one is rougher than the other, the high spots which make contact with the opposite surface will mostly be on the rougher surface, and though the rubbing may be apparently symmetrical there should be a separation of charge resulting in the two bodies becoming electrified as if they were made of different materials. It has been observed before (e.g. Shaw[6]) that materials with a matt surface tend to occupy a different position in a triboelectric series obtained by rubbing from that of the same material with a smooth surface.

The author has made a few experiments in which a number of pieces were cut from a single sheet of an insulating material having a smooth surface, and some of these were roughened by rubbing them with different grades of glass paper. All the samples were then scrubbed under water to get rid of debris, wiped with a clean cloth, and allowed to dry. All possible pairs of samples of a given material were lightly rubbed together with a symmetrical circular motion, and both samples of each pair tested for charge by presenting them in turn to within a centimetre or so of the exposed input socket of a Baldwin–Farmer electrometer. The materials used were Perspex, ebonite, Silvanite, and plate glass. (The last was, of course, ground with carborundum powder, not glass paper.) In every case appreciable, and reproducible, separation of charge occurred, and it was found possible to arrange the three or four samples of each material in a self-consistent triboelectric series with the smooth sample always by a good margin at one end of the series. In the case of Perspex the smooth sample was negative to the rest; in the other three cases the smooth sample was always the most positive. The order in which the roughened samples occurred showed no significant correlation with the grade of the abrasive used. Possibly the extra number of corrugations per unit area produced by the finer abrasives often offset their lower height.

This phenomenon would provide an alternative explanation for an observation by Martin[7] in connexion with wool fibres. If a bundle of wool fibres all oriented similarly (i.e. tips in one direction, roots in the other) is held firmly, and single fibres are withdrawn by means of forceps, the fibres pulled out are found to be charged positively or negatively according as the fibre is pulled out by the root end or by the tip end. This was attributed by Martin to a piezoelectric effect in the scales which form the surface of the fibre. These scales have their tips projecting in one direction like the teeth of a ratchet, and it is reasonable to suppose that a fibre which was being pulled in a direction against its own ratchet teeth would receive its rubbing in a more concentrated form at the tips of the teeth than the surrounding fibres, which would be rubbed in the easy direction of their teeth. Thus a separation of charge would be likely to occur even if the scales were not piezoelectric, and its sign would be reversed with the direction of withdrawal of the fibre.

(3) When two different materials are rubbed together, as in the majority of the triboelectric experiments in the past, a combination of the "equilibrium" and "kinetic" processes will take place. The direction of charge separation at any one spot may depend upon the local geometry of the surfaces as described above, as well as upon the overall manner of rubbing (which has often itself been very asymmetric). Hence it is not surprising that the results are apt to be erratic unless the conditions are devised with the object of isolating the "equilibrium" process by doing away with friction as far as possible.

(4) It has been observed by Shaw[3] that if two bodies of identical material are caused to strike each other a violent glancing blow, a separation of charge between them may occur, but that the charges on the two bodies, although opposite in sign, are not equal in magnitude. The difference, he pointed out, must have escaped to the air either as ions formed in the air or as minute particles of the solid thrown off. He subsequently[8] confirmed this phenomenon as produced when powders are blown against a surface of the same nature, or simply blown out into the air so that particles strike against each other. Similar observations have been made by Rudge[9] and Gill,[10] and these phenomena are held to account for the electrical disturbances often occurring in dust and sand storms. The explanations put forward by Shaw and by Gill to account for the charges carried by the air both assumed the production of minute particles from the solids, one author postulating a minute "explosion" caused by the local heat of impact. This may present a true picture of the occurrence, but an easier explanation has become available since Cox and Peace[11] and Medley[12] have pointed out the important role of electrical breakdown of the air in limiting charge densities on surfaces that have just separated. Normally the discharge starts as soon as the distance between the surface is a few mean free ionic paths in air, and the effect is simply to provide a conducting path whereby the

charges on the solid surfaces can partially neutralize each other. In asymmetric rubbing of the sort we are considering, however, the charge density on the "rubber" may not accumulate to the point of breakdown till some of the opposite charge on the "rubbed" surface is too far away to take part. It seems reasonable to suppose that a one-sided discharge from the "rubber" may then occur, resulting in a true ionic charge being imparted to the air. It is not necessary for this explanation that the two surfaces should be of the same material, but if the materials are different the limiting charge density is likely to be reached with less relative motion, and the effect of the asymmetric rubbing will be less apparent.

THE "EQUILIBRIUM EFFECT"

If this is of the nature of a contact potential, as suggested by Helmholtz, and if it can be produced separately from other effects, it should be additive in the sense that for equal true areas and distances of contact, and in the absence of discharge in the gas between the separating surfaces, the charge on a surface *A* after contact with a surface *C* should be equal to the algebraic sum of the charges on *A* after contact with *B*, and on *B* after contact with *C*. In practice it is difficult to avoid the complications connected with contact area and gas discharge except in particular cases, and with relatively elaborate apparatus. However, if we do not expect quantitative results, there is none the less an interesting and well known consequence of Helmholtz's hypothesis which can be tested—that if the mechanism he suggested is the only one operating under the circumstances of the experiment, it should be possible to arrange any set of surfaces in a self-consistent series such that any surface becomes positively charged after contact with another below it in the series (and therefore negatively charged after contact with one above it). This would be a consequence of any other theory involving equilibrium processes only, but not necessarily of theories postulating kinetic processes. In testing this prediction from Helmholtz's hypothesis we are not likely to be troubled about the uncertainty of true contact areas, or by gas discharge, since it is improbable that either of these factors would reverse the signs of the charges. We have, however, according to the ideas expressed in this paper, to avoid friction in order to confine the phenomena to equilibrium processes. Some who have looked for the existence of electrostatic series by experiments involving rubbing have eventually reported results inconsistent with such a series.[1]

The author has experimented with a number of substances available in sheet form, both insulating and conducting. The method was simple, and was intended to minimize friction. It was originally designed also to imitate the many industrial processes in which a sheet or yarn is passed between rollers, but it has proved convenient for "academic" work as well. It probably does not entirely eliminate friction, but none the less this is very much reduced compared with the type of experiment in which materials are intentionally rubbed together.

The procedure was to make up a sandwich of one piece of *A* between two of *B*, to pass this between a pair of steel rollers under a deadweight load, and to measure the charge on *A* (the "meat" of the sandwich) by separating the samples with amber-tipped forceps and dropping *A* into a well-screened Faraday cylinder connected to a Baldwin–Farmer electrometer. It would have been of no use measuring the charge on *B* (the "bread" of the sandwich) since this had been in contact with the rollers as well as with *A*. However, another sandwich was then made up with one piece of *B* between two of *A*, and the process repeated. Thus each pair of materials was tested twice, the charge on each member of the pair being determined. As each sandwich was made up, its constituents were discharged by means of a small radium source and tested for neutrality by plunging them into the Faraday cylinder. Three pieces of each material were prepared: two pieces 12×5 cm for use as the outside of one sandwich, and one piece 10×3 cm for the inside of the other. The difference in size was intended to prevent all possibility of the inner sample coming into contact with the rollers, but it had the disadvantage that the samples used for a given material in the two experiments with each pair were different. It was in fact found in many cases that the small sample of a given material, when passed through the rollers between the two large pieces of the same material, developed considerable charges. These were found to be quite consistently repeated, indicating that there was some definite difference between the surfaces of the small and large samples in each case, and corrections were made to some of the results accordingly, as described below.

The samples were such as were immediately available in continuous thin sheet form (except the filter paper). All were the ordinary commercial product. Three metals were included: platinum as a noble metal likely to carry less oxide than most, aluminium as an active metal protected by a coherent invisible film of oxide, and copper as a metal which had originally been cleaned with emery paper but had, by long standing in clean air, become very visibly tarnished. The cellulose acetate and triacetate were, respectively, Courtauld's commercial acetate sheet and the material made by Bexford Ltd. for use as the base of photographic films (but not "pretreated," "subbed," or "blue-dyed"). Both probably contain a fair proportion of plasticizer. The Formvar (polyvinyl formal) and polystyrene were thin foils supplied by Hordern-Richmond Ltd., and B. X. Plastics Ltd. They may contain a little plasticizer, but probably not much. The polythene was Alkathene sheet supplied by I.C.I. Ltd. It probably contains no plasticizer. The rubber was dental "rubber dam." The filter paper was Whatman No. 1.

Some of the materials which were visibly dirty were first washed with soap and water, rinsed for a minute or two in soft tap water, wiped with a clean towel, and allowed to dry. From this point onwards they were never touched again by the fingers, being always handled with metal or amber-tipped forceps. All samples except the filter paper and rubber were then immersed in petrol ether (60–80° C), rubbed with a previously "extracted" brush, drained quickly, and blotted dry with filter paper. The rubber was similarly washed with absolute ethyl alcohol. The filter paper samples were used without preparation. All samples were subsequently kept by themselves in boxes lined with filter paper. It is realized that this preparatory treatment was not particularly thorough (see, for instance, the experience of Shaw and Jex[13]), but time was short and the object of the experiment was not to ascertain a characteristic order for the various materials, but solely to see if with a given set of samples, using contact with the minimum of friction, and testing all possible pairs, it was possible to find a self-consistent series.

Preliminary experiments showed that handling the samples with forceps could not have produced a charge greater than 2 e.s.u. in the worst case (rubber), and that the charge produced thus would in most cases have been only a fraction of a unit. These will be seen to be negligible compared with the charges produced by rolling. It was also found that a metal sample could be held in the amber-tipped forceps without

appreciable loss of charge for a much longer time than occurred in the experiment.

Out of the ten different materials all possible combinations were used, except that there was no point in doing metal-against-metal experiments. The relative humidity of the atmosphere in the room at the time was low enough for the filter paper samples to be treated as insulators, though no time was lost in separating filter paper-metal sandwiches once they had been through the rollers. It will be noticed from the table, however, that the charges from these sandwiches were low and irregular.

The figures in the table are the charges, in absolute electrostatic units, found on the inner samples of the sandwiches. sample was of metal. Each row corresponding to a metal was multiplied by a factor to bring the sum of the charges (irrespective of sign) equal to that in the vertical column for the same metal. This may not be a strictly accurate way of applying the correction, but at least it cannot change the signs, which are the chief point of interest in this table. It is hoped that by a modification of the technique it will be possible in the future to dispense with these corrections (see below).

During the experiment the relative humidity varied from 38 to 37% and the temperature from 22° to 23° C.

The materials in the table have been arranged in the correct order as shown by the results, hence the criterion of a

Charges (in e.s.u.) on 10 × 3 *cm "sandwich" samples after passage between rollers*

In contact with: / *Charges on:*	*platinum*	*Formvar*	*filter paper*	*cellulose acetate*	*cellulose triacetate*	*polythene*	*aluminium*	*polystyrene*	*copper (tarnished)*	*rubber*
platinum	0	18	32	110	21	99	—	50	—	79
Formvar	−16	0	15	(−7)	25	123	31	9	22	118
filter paper	−14	−4	0	5	25	106	5	24	10	76
cellulose acetate	−78	−12	−5	0	13	97	55	109	75	158
cellulose triacetate	−79	−34	−23	−38	0	67	35	67	59	110
polythene	−86	−62	−98	−83	−82	0	68	3	133	115
aluminium	—	−19	**(16)**	−110	−18	−67	0	73	—	67
polystyrene	−64	−27	−19	−83	−90	**(5)**	−32	0	10	105
copper (tarnished)	—	−38	−5	−111	−92	−39	—	−39	0	68
rubber	−73	−121	−105	−207	−189	−128	−103	−138	−90	0

In most cases they represent the means of several readings. The scatter was considerable, say ±20%, but appeared to be a true percentage scatter; that is to say, the variation in units of charge was smaller the smaller the value of the charge. Only one reading out of the 200 to 300 made differed in sign from other readings of the same quantity, and this was a very small charge (7 units). This type of scatter, which is by no means the rule in electrostatic experiments, suggests that a single phenomenon has been allowed to predominate by dispensing with rubbing, and that the scatter may be chiefly due to variation in contact area and gas discharge.

It has been mentioned that in some cases considerable charges (up to 40 e.s.u.) were obtained when the inner and outer materials were the same, indicating some accidental difference between the samples of a given material. The readings in the table below have been corrected for this by adding to or subtracting from each reading in each vertical column a quantity sufficient to bring the charges on the diagonal row of readings to zero. This should have the effect of converting all charges obtained with a given pair of outer samples to the values which would have been obtained had these samples the same properties as the small pieces of the same material. This could only be done for the columns corresponding to insulators, for it would be useless testing a metal against itself. The corrections for the three metal columns were worked out on the assumption that the mean charge (taking account of sign) in the vertical row for a given metal should be equal to that for the horizontal row for the same metal but with the sign reversed. Before this correction was made, however, each horizontal row for the three metal samples was corrected for the loss of charge by discharge from corners and edges of the metal inner samples as the sandwich was separated. That such loss occurred was indicated by the very low charges found when the inner self-consistent series is that the charges on one side of the diagonal line of noughts should all be positive, whilst those on the other side should all be negative. It will be seen that only three out of the eighty-four non-zero figures disobey this rule, and that two of these are very small charges lying next door to the line of noughts (these are Formvar against cellulose acetate, and polystyrene against polythene). Only one (aluminium against filter paper) is outside the limits of probable error. This pair persistently gave definite positive charges on both members. This was probably due to loss of negative charge by discharge in air from the corners and edges of the aluminium sample, followed by leakage to it of positive charge from the poorly conducting filter paper.

It is not claimed that these results prove anything. It is perhaps permissible to say that they are suggestive of an equilibrium phenomenon.

It is not intended to comment on the order of the different materials in the series at present, as the preparation of the surfaces was not sufficiently thorough to make this worth while. The author intends, as soon as time permits, to repeat the experiment with more thorough precautions, using identical surfaces in both inner and outer positions in the sandwiches. This will involve having all samples the same size and accurately placed upon each other, and it may prove impossible to include the metals as inner samples.

It would be expected that the magnitudes of the charges would increase the further the entry is from the line of noughts in the table. In general this is found to be so, but there are many exceptions. It must be remembered that the true areas of contact probably varied with different kinds of samples, and that discharge through the air was very audible during the separation of many of the sandwiches. Once a discharge has started, it is likely that the charge densities on the surfaces may be reduced below the level at which a discharge would just not have started.

THE "KINETIC EFFECT"

This effect, so far as the author's experiments indicate, can be demonstrated with any of the usual highly insulating materials, most conveniently in rod form. The method is similar to that described by Shaw.[3] Two similar rods are grasped by the end, one in each hand, and tested for neutrality by plunging their free ends into a deep well-screened Faraday cylinder connected to an electrometer. If necessary, they are discharged by passing them close to a small radium source. They are then rubbed on each other in such a way that the rubbing is confined to one spot on rod *A*, but spread out over the length of rod *B*, or *vice versa*. This is illustrated in Fig. 2. The rods are then tested by means of the Faraday

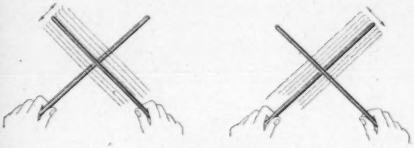

Fig. 2. Asymmetric rubbing

cylinder as before. It will be found that they are oppositely charged, and that the charges reverse when the respective roles of the two rods are reversed.

Shaw attributed this effect to a permanent difference in the states of strain of the two surfaces set up by the rubbing, thus producing what in effect were two different surfaces. This may be part of the story, but does not account very well for the immediate reversal of charge if the rods are discharged and rubbed again in the opposite sense. Shaw also remarked that the heat generated by the rubbing would assist recovery from strain. Frenkel[14] suggested that the separation of charge when *different* substances were rubbed together was due to a pyroelectric effect brought about by the local heating. This would presumably only apply to crystalline, or at least orientated, materials. The author believes that the local heating is indeed the cause of the effect that we are discussing, but in a rather different way from those suggested by Shaw and Frenkel. (Reference may be made to the work of Bowden[15] and his colleagues to show the surprising temperatures which can be reached in quite light rubbing.) The author's theory requires no *ad hoc* hypothesis as to the nature of the surfaces or the effect of strain on their affinity for charged particles.

The separation of charge between two identical surfaces seems to require that the friction should be concentrated onto a smaller area of one surface than of the other. This would give rise to a strong temperature *gradient* across the interface as the already hot spot on one surface continually met fresh cool parts of the other surface. This temperature gradient would result in a larger number of mobile particles (whatever their nature) migrating from the hot to the cold side of the boundary than in the opposite durection. If mobile particles having a charge of one sign are either more numerous or of smaller mass (and therefore higher average velocity) than the particles of the opposite sign, there will be a net passage of charge across the boundary which will continue until an electrical potential difference has been set up sufficient to equalize the migration rates. The phenomenon would be analogous to the thermal diffusion of gas molecules through a porous plug from the hot to the cold side of a container, in which case the net migration ceases when a certain pressure difference has been set up. Perhaps a closer analogy is afforded by the Thompson thermoelectric effect in metals, which indicates that a small electric potential difference exists between the two ends of a piece of metal held at different temperatures, and is due to the increased thermal velocity of electrons coming from the hot side. There may also be an additional component of contact potential difference between the hot and cold ends of the metal resulting from a change of "work function" with temperature. (This component would not appear in the Thompson effect as usually measured—the "specific heat of electricity"—since the work done *by* an electron due to the difference in "work function" in going from one end of the metal to the other would be exactly balanced by the work done *on* the electron by the corresponding component of the electrostatic potential difference.) Whether there is an effect of this sort occurring during the asymmetric rubbing of two insulators, the author would not like to guess.

Whatever the exact mechanism by which a temperature gradient is supposed to cause a net migration of charge across the boundary, it should be possible to check by experiment the hypothesis that such an effect exists. Shaw and Jex[16] stated that a warm glass rod rubbed on a cold one produces a definite separation of charge which reverses on rubbing when the other rod is warmed and the first is allowed to cool. They had, however, a perfectly reasonable explanation of this in terms of moisture from the atmosphere, which is driven off on warming and redeposited on cooling. The author hopes to do this type of experiment in a dry atmosphere as soon as opportunity offers. It is not possible to look for the effect by means of "sandwich" experiments without rubbing, as described earlier in this paper, since when a hot body is brought into *stationary* contact with a cool one the temperature gradient at the interface becomes negligible in a very small fraction of a second. A much steeper gradient is maintained where rubbing continually brings fresh hot and cold surfaces into contact with each other. It would be desirable to look for the effect in the absence of rubbing, however, and the author hopes shortly to attempt this by causing a small sphere of an insulating material to bounce off a block of the same material at a different temperature. The time of contact could be cut down by this means to less than a millisecond. The collision would itself, no doubt, produce a local rise in temperature. The object of the experiment would be to investigate the effect of differences in initial temperature between the sphere and block.

ACKNOWLEDGEMENT

I wish to thank the Director and Council of the British Cotton Industry Research Association for permission to publish this work.

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DISCUSSION

Mr. J. M. Wolstenhulme: Various workers have produced triboelectric series, as Dr. Henry has described, which have included hygroscopic materials such as paper, with which I am concerned. They do not all show the same sequence. Does the position of such a material in a series depend on its moisture content?

Also, Dr. Henry has demonstrated the distribution of positive and negative charges on a surface at the same time, using the method described by Hull. We have tried this method but could not obtain consistent results. Did Dr. Henry use lycopodium and flowers of sulphur, and how did he charge up the mixture?

Dr. A. E. Kay: Dr. Henry omitted to mention some later work by P. E. Shaw in which it was shown that the polarities of the charges on the rubber and rubbed bodies could be reversed by continued rubbing. Furthermore, it was demonstrated that the rubber and rubbed bodies returned to a state in which they could produce the original polarities on rubbing provided they were left undisturbed for some time. I believe it was on the basis of these later experiments that Shaw used the broad interpretation in terms of strain rather than temperature.

Mr. G. King: In the case of ionic semi-conductors I wonder whether it might be possible to combine the Helmholtz contact potential and the temperature effect produced by asymmetric rubbing by saying that the potential is present whenever there is a difference in chemical potential across the surface of contact. This will be modified by a diffusion potential for ionic transfer produced by the different mobilities of the ions present. The latter effect produces complications except in the case of contact between long chain compounds such as in exchange resins where one ion is firmly bound to the hydrocarbon chains. Other compounds donate the mobile ion, i.e. strongly acid resins donate protons and develop negative charges as shown recently by Medley.

Mr. K. W. Mieszkis: Would Dr. Henry accept the following explanation of the phenomena taking place during the asymmetric rubbing of the two identical materials?

If we rub two rods A and B of the same material each (say) of a square cross-section of 1 cm^2 in such a way that rod A is rubbed only in one place on the surface of 1 cm^2 and rod B along a length of 10 cm then, according to the asymmetric rubbing rule, one of the rods will acquire a positive and the other a negative charge.

When we think of flat surfaces we can always find a suitable magnification which will show that these so-called flat surfaces are covered with hills and valleys and on two identical rods we can assume that on 1 cm^2 there will be, say, n hills. During the asymmetric rubbing of the rod A, n hills of its 1 cm^2 surface will come in contact with $10n$ hills of the rod B, and there are some reasons to believe that on average each hill of the rod A will be struck 10 times more during this asymmetric rubbing than a hill on the rod B.

To simplify the picture let us think that one hill on the rod A is like a block which receives blows from 10 identical hammers representing the hills on rod B. Block and heads of hammers are identical; made of the same material, same mass and shape and at the same temperature T. When the first blow was delivered the block and the hammer should be in an identical state with their temperature only increased to $T + dT$, but when the second blow is delivered the block representing a hill of the rod A will have a temperature of $T + dT$ and it will receive a blow of another hammer representing a second hill from the rod B at a lower temperature T. After each blow on the block representing a hill on the rod A its temperature will rise as it comes in contact with another hammer representing the hills on the rod B which will be still at the original temperature T.

I suggest that during asymmetric rubbing we are creating a difference of temperature between the two rubbing surfaces which is responsible for the transfer of electrons and the formation of different charges on the two rods.

Mr. G. S. Rose mentioned experiments to show the existence of an electrostatic series involving both insulators and metals. Electrification, which was done merely by contact (with frictional effects reduced to a minimum), was measured and the effect of the roughness of the surfaces used was investigated. Experiments to examine the additive property of the charging produced were at present in progress.

Author's reply: Replying to Mr. Wolstenhulme, it seems likely enough that the moisture content would affect the position of hygroscopic materials in the series. This is an important point, but I cannot remember seeing any data bearing on it.

I, too, had difficulty in getting reliable results with the powder mixtures. The example shown on the screen was done with a mixture of carmine powder and undyed lycopodium only. I found that it helped to have everything warm and dry before starting—perhaps the Americans worked in a drier atmosphere than we. The techniques used in "xerography" should give a useful pointer, but I have not followed up this idea yet.

In reply to Dr. Kay, the work in question was mentioned in the printed version of my paper, if not in the spoken version. The truth is probably that both effects take place together; the reversal of sign that you mention itself suggests the presence of two effects. I am emphasizing the thermal gradient hypothesis because it appears to be new, and because theory suggests that an effect of this sort must take place, but it does not exclude the other effects. This outlook I have expounded in more detail in an article in *Science Progress*.*

In reply to Mr. G. King, I think that it would be unwise to apply to such very local phenomena concepts developed for use with extended phases and surfaces. In particular, I do not think that the notion of mobility is applicable to an ion crossing over between two solid surfaces. I prefer the elementary kinetic considerations suggested in my introductory survey to this session as a means of collecting together into the same picture several of the various mechanisms that have been proposed.

The picture Mr. Mieszkis gives forms a fair description of the ideas I put forward in my paper.

I am looking forward to seeing an account of Mr. Rose's experiments.

* Henry, P. S. H. *Sci. Progr.*, **41**, p. 617 (1953).

Methods of increasing the electrical conductivity of surfaces

By J. S. Forrest, M.A., D.Sc., F.Inst.P., British Electricity Authority Research Laboratories, Leatherhead

Difficulties due to electrostatic charges on insulating surfaces can be overcome by coating the surface with an electrically-conducting film. The paper describes conducting films of metallic oxides, metals, carbon, moisture and wetting agents. Information is also given on the application of these films to ceramic and plastic insulating materials.

The generation of static electrification is a surface phenomenon so that the amount and polarity of the charge generated, and the rate at which it is dissipated, are dependent on the nature of the surfaces in question. Difficulties due to electrostatic potentials can be overcome by reducing the rate of charge generation, or by allowing the charge to leak away by treating the surface to reduce its electrical resistance. It is with the latter aspect that this paper is concerned, although it is probable that some of the surface treatments described may also have an influence on the rate of charge generation.

It should be remembered that, in addition to reducing the resistance of the electrified surface, it may also be necessary to provide a conducting circuit to enable the charge to be neutralized, or to flow to earth. A static charge can occur even on metal parts if they are highly insulated. Sometimes an oil film in a machine has the effect of allowing a static charge to build up.

The rate of dissipation of charge (or voltage) is given by the well-known relation:

$$Q = Q_0 \exp(-t/RC)$$

where Q_0 is the initial charge, Q the charge after t seconds, R the circuit resistance in megohms and C the effective capacitance in microfarads. Thus the time of discharge is directly proportional to the circuit resistance. The "time constant," RC seconds, is the time in which the charge falls to $1/e$, or 36·8%, of its initial value, and is used as a measure of the rate of dissipation of the charge.

If the static charge is generated continuously, as in a belt-drive, then a steady value of charge (and voltage) will be attained when the rate of charge generation is equal to the rate of dissipation. The steady value of the charge will, however, still be proportional to the time constant. Thus a reduction in the leakage resistance will reduce the charge proportionately. The actual value of resistance required to reduce the charge to a given level depends on the rate of generation of charge, but in most practical applications quite a high value of surface resistivity, of the order of hundreds of megohms, will suffice. (The surface resistivity is the resistance between opposite sides of a square; it is independent of the size of the square.)

In the following sections a description is given of various surface films and treatments which are effective in increasing the conductivity of insulating surfaces. Some of these methods were developed with other applications in view but may nevertheless serve for the dissipation of static charge. It should be noted that the resistance of many of the films described will vary with temperature and with the current flowing in the film. These effects are usually not important for the present purpose. It is important, however, that the film should retain its electrical continuity in service. Many of these thin films are not very durable and it is desirable to check the electrical resistance from time to time. Discontinuities are particularly liable to occur at the points where contact is made between the film and a metallic electrode.

The type of surface film to be selected for a particular application depends largely on the basic material on which the charge is generated and on the conditions under which the material is used.

Surface films based on metallic oxides

Semi-conducting ceramic glaze. An interesting method of reducing the resistance of a porcelain surface consists in coating it with a semi-conducting glaze.[1,2] These glazes are applied to the porcelain base in the same way as ordinary glazes, and have a similar basic composition, except that they contain a much higher proportion of metallic oxides, e.g. Fe_2O_3, ZnO, Cr_2O_3, which give the glaze its conducting properties. Such a semi-conducting glaze has a smooth, durable, vitrified surface, and is similar in appearance to an ordinary brown glaze. Surface resistivities can be obtained over a wide range from say 0·2 to some hundreds of megohms. A comparative figure for a clean, dry, porcelain surface with a normal glaze would be about 100 000 MΩ.

Photomicrographs of sections of typical non-conducting and semi-conducting glazes are shown in Fig. 1. Fig. 1(*a*)

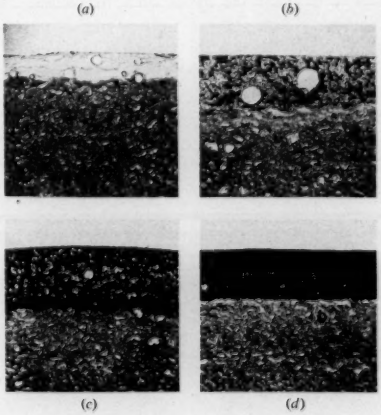

Fig. 1. Photomicrographs of ceramic glazes (× 50)

(*a*) Non-conducting clear glaze.
(*b*) Non-conducting brown glaze.
(*c*) Semi-conducting glaze (normal resistance).
(*d*) Semi-conducting glaze (low resistance).

shows the clear glassy structure of a non-conducting transparent glaze. A brown glaze containing metallic oxide particles but still non-conducting is shown in Fig. 1(*b*). Fig. 1(*c*) is a semi-conducting glaze containing a larger proportion of metallic oxides which now form a continuous conducting network in the glaze having a surface resistivity of about 10 MΩ. Finally Fig. 1(*d*) shows a very low resistance

semi-conducting glaze (surface resistivity 1 MΩ); it still retains its glassy structure but is now almost completely opaque.

Stannic oxide films. Transparent conducting films of stannic oxide can be produced on glass and other ceramics by spraying tin chloride on to the heated surface of the glass. This process has been used commercially in the United States to produce glass with a conducting film which can be electrically heated to prevent condensation or icing. In this country, similar metallic oxide films have been developed at the National Physical Laboratory using a cathodic sputtering process.[3,4] Surface resistivities of from 100 to several thousand ohms can be obtained. These films, being transparent, should be particularly useful for screening instrument movements from charges on the glass dial or from stray electrostatic fields.

THIN METALLIC FILMS

Metal spraying. Thin films of many metals can be applied to porcelain, glass, plastics and other materials by various methods, such as spraying, sputtering or evaporation in a vacuum. Very low resistivities can be obtained, of the order of a few ohms, but difficulties often arise in practice owing to the lack of adhesion between the metallic film and the base material. It should be noted in passing that some "metallic" films have a high resistance—ordinary aluminium or "gold" paint, for example, is a good insulator.

Lead films. An interesting method of forming a conducting film of metallic lead by heating lead silicate glass in an atmosphere of hydrogen has been described by K. B. Blodgett.[5] The surface of the glass becomes blackened, due to the separation of metallic lead, and a film is formed which has semi-conducting properties. The method is not suitable if very low resistivities are required but values of the order of 1000 MΩ are easily obtained. A similar treatment can be applied to porcelain.

FILMS BASED ON CARBON

Colloidal carbon dispersed in aqueous or other media can be applied to almost any surface and will give a conducting film having a resistivity of, say, a thousand ohms to several megohms. The lower values are obtained by applying several coats or using more concentrated dispersions. Burnishing the film gently also helps to reduce its resistance.

Electrically conducting paints containing finely divided carbon (particle size, less than 1 μ) are also available. The carbon may be dispersed in an oil base as an ordinary oil paint, or in a synthetic resin base giving a paint suitable for stoving after application. Surface resistivities of from a small fraction of a megohm up to several megohms are stated to be obtainable but such coatings are often unreliable, as the conducting particles may be isolated in the insulating medium which forms the base of the paint. In practical applications, the resistance should always be checked by measurement.

Another method of preparing a carbon film is that used for the manufacture of high-stability "cracked" carbon resistors. The carbon is deposited on porcelain at a high temperature from a gaseous hydrocarbon. The surface resistivity lies between 100 and 10 000 Ω.

Although not usually used in the form of a surface film, conducting rubber should be mentioned here. This is rubber loaded with finely divided carbon black; it is available with a range of *volume* resistivity of from 2·5 to 10^8 Ωcm.[6] As might be expected from the nature of the material, the resistivity of conducting rubber changes, temporarily or permanently, if twisted or stretched. For antistatic applications, e.g. motor tyres or conducting flooring, a resistivity of 0·1 to 1 MΩcm is used. Coatings of conducting rubber, which could be applied as a rubber solution, might, however, be used in other cases where it is necessary to dissipate static charges.

MOISTURE FILMS

Surface films of moisture form very readily on certain materials, and reduce the surface resistivity. Different materials exhibit this effect in very different degrees; polythene, for example, is not very susceptible but glass and glazed porcelain show the effect very strongly. The value of the surface resistivity depends on the relative humidity of the atmosphere and on the cleanliness of the porcelain surface. Thus clean dry porcelain in an atmosphere of 50% relative humidity has a surface resistivity of about 100 000 MΩ. As the relative humidity increases the surface resistivity decreases rapidly, the decrease becoming particularly marked when the relative humidity exceeds 70%. When the humidity reaches 90% the resistivity is of the order of 1000 MΩ. Much lower values are obtained when the porcelain surface is soiled; typical figures for a surface exposed to a polluted atmosphere are 100–100 000 MΩ at 50% relative humidity and 1–10 MΩ at 90% relative humidity.

These moisture films are rather unstable as the resistance varies over such a wide range with variations of humidity; moreover, the surface film takes some time to attain a state of equilibrium after a change in atmospheric humidity. It is clear, nevertheless, that at the higher humidities the surface resistance is low enough to dissipate static charges, and it is well known that difficulties due to static potentials can often be avoided by increasing the humidity of the atmosphere. It should be noted as a broad rule that the resistivity usually begins to decrease sharply at about 70% relative humidity so that it is necessary to increase the relative humidity to not less than 70%. A further point to be borne in mind is that

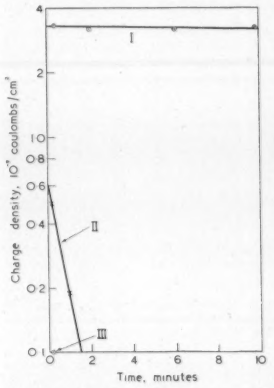

Fig. 2. Effect of wetting agents on the electrification of perspex

I. Clean dry perspex.
II. After treatment with Shell Teepol 530.
III. After treatment with I.C.I. Lissapol N.

if an appreciable current flows in a moist surface film it may dry the film and increase the surface resistance.

FILMS OF WETTING AGENT

It has been pointed out by B. H. Parks[7] that the formation of static charges on perspex and other plastic surfaces can be prevented by treating the surface with a wetting agent such as I.C.I. Lissapol N. Fig. 2 shows the results of some experiments, which demonstrate this effect. The experiments were made on a highly-insulated disk of perspex, 10 cm in diameter, which was electrified by rubbing with silk. The charge density after various time intervals was measured with a portable electrometer.[8] It is seen that the untreated perspex lost its charge only very slowly—in fact the time constant was several hours. A similar disk of perspex treated with I.C.I. Lissapol N, allowed to stand for 24 h and then electrified by rubbing, had a much smaller time constant, of the order of a few seconds, and the charge was too small to measure accurately. For practical purposes the perspex could not be electrified. The effect is quite lasting—for at least several weeks in a normal atmosphere—but repeated rubbings will remove the film and the material will regain its original electrification properties. Fig. 2 also shows the effects of another wetting agent of different constitution—Shell Teepol 530. It has a similar action but is not as effective, the time constant being about 1 min.

Measurements of resistance showed that the surface film produced by the wetting agents reduces the resistivity by a factor of several thousand. It appears, therefore, that the antistatic effect is partly due to the reduction in surface resistance; the surface film may, however, also inhibit the generation of static charge as the results indicate that the initial charge was reduced after treatment.

ACKNOWLEDGEMENTS

The photomicrographs (Fig. 1) were prepared by E. A. Phoenix, and the experiments with wetting agents were made by A. W. Stannett, at British Electricity Authority Research Laboratories, Leatherhead.

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DISCUSSION

Dr. A. Bracken: We have found that applying surface-active conductive films to thin polyvinyl chloride sheeting did not always remove the possibility of generating a charge on it. The relative humidity was critical for success because all these agents act by attracting a film of moisture. In general the relative humidity indoors was too low for the method to be successful and it was abandoned.

Author's reply: I agree that the relative humidity is an important factor and that the main effect of the surface-active agent is to form a continuous conducting layer of moisture on the surface. The detailed mechanism is more complicated, however, as the surface-active agent may also affect the generation of charge. In fact we have noticed that after some surface treatments the polarity of the charge is reversed.

The physics of electrostatic precipitation

By H. J. Lowe, B.Sc., and D. H. Lucas, B.A., A.Inst.P., British Electricity Authority Research Laboratories, Leatherhead

This paper summarizes the existing theories of the behaviour of particles in an electric field with special reference to the electrostatic precipitation of flue dust in power stations burning pulverized coal. The theoretical relation between particle size and precipitation efficiency is not borne out in practice and an endeavour is made to resolve the discrepancy by considering the molecular and electric forces acting on particles after they have been deposited on the collecting electrodes.

One of the most important uses of static electricity is the collection of fine airborne powders and mists in the cement, carbon black, sulphuric acid, steel, gas and other industries. The largest single application is undoubtedly the cleaning of flue gases from the large boilers used in the generation of electricity. This paper is a survey of the theory of electrostatic precipitation, with particular reference to the extraction of flue dust in the electricity supply industry.

A certain amount of ash, generally termed "fly ash," is inevitably carried out of the combustion chambers of power station boilers by the flue gases in the form of dust and grits. In the travelling grate type of boiler employing forced draught and burning small coals, about 10–20% of the ash is entrained in the flue gas, but normally the majority of the particles are coarse and may be readily removed by cyclone separators before the gases pass out of the chimney.

Much more difficult conditions were encountered with the introduction of pulverized fuel fired boilers. In these the coal is ground to a very fine powder (about 80% through a 200 mesh sieve) which is continuously blown into the furnace and burned. Whilst some of the coarser particles will settle in the combustion chamber and fall into the ash hoppers, the remainder will be carried out with the flue gases. The proportion of fly ash will vary with boiler design and operating conditions, but is usually about 50–75%, though it may be as high as 85% in large modern installations. Thus, a station burning 2000 tons of coal daily with, say, 12% ash content might produce as much as 200 tons of flue dust every day. It is desirable to reduce the dust burden of the flue gas to an innocuous level—about 0·5 g/m^3 at N.T.P.—and, for this purpose, plant capable of removing about 98% of the suspended dust is required.

Because of the fine grinding of the coal, the particles of fly ash are extremely small, and approximately 50% by weight of the dust consists of particles of less than 20 μ diameter. To extract such small particles by cyclone separators would require an unduly high pressure drop. Washing the flue gas by passing it through water sprays is possible, but the method has several undesirable characteristics. In this country, electrostatic precipitators are fitted at power stations operating the pulverized fuel type of boiler, and this method of dust extraction has the following advantages.[1]

1. The flue gases do not come in contact with water.
2. The flue gases are not cooled appreciably before being passed to the chimney.
3. Draught loss is very small—about $\frac{1}{2}$ in. w.g.
4. Auxiliary power consumption is low—about 2–5 kWh per million ft^3 of gas treated.
5. Maintenance costs are low.
6. The dust is collected dry and can be removed either wet or dry.

On the other hand, capital costs are fairly high—the current annual capital expenditure of the British Electricity Authority on electrostatic precipitators alone is about £2$\frac{1}{2}$ million.

It should perhaps be mentioned that on several of the latest installations the electrostatic precipitators have been supplemented by a multi-cell type cyclone unit of moderate pressure drop which is located before the precipitator. By removing the coarser grits this unit avoids overloading the electrostatic precipitators at the very high dust concentrations which may occur during periods of soot-blowing, and may actually improve its efficiency by reducing the re-entrainment of dust into the gas stream.

GENERAL PRINCIPLES OF OPERATION

Industrial precipitators consist essentially of a series of earthed parallel plates or tubes through which the dust-laden gases are passed. In either case the earthed surfaces enclose wire electrodes which are raised to a high, usually negative, potential. Corona discharge at these electrodes causes ions to traverse the intervening space and to charge the dust particles. The charged particles move towards the earthed electrodes under the influence of the electric field and are deposited there. In accordance with their functions, the wire is generally termed the "discharge electrode" and the plates or tubes the "collecting electrodes." The collected dust is shaken from the electrodes, by occasionally rapping them with hammers or electromagnetic vibrators, and falls under gravity into hoppers. The electrodes are vertical and in the case of plate type precipitators, the gas flow is usually horizontal. Plate type electrodes are usually fitted with louvres and it is claimed that these remove the precipitated dust and allow it to fall into the hoppers without interference from the main gas stream. If appropriately designed they may also make a considerable contribution to the collection of large particles and aggregates by impaction.

In some cases the functions of particle charging and collecting are carried out separately in successive chambers. This arrangement is usually applied to air cleansing where only very small particles are concerned.

The potentials employed are of the order of 40 kV and are commonly provided by step-up transformers followed by rectifiers of the mechanical or selenium cell type. There are two schools of thought regarding the best waveform to be used. Some favour a smooth waveform, in which case the current will be continuous. This offers obvious advantages but introduces the danger of sustained arcing. Recently, 100 μsec pulses of voltage recurring some hundreds of times a second have been used. The peak voltage allowable is very much higher than the steady flashover voltage and greatly improved efficiencies are claimed.[2] The waveforms normally used are a compromise between these two extremes.

In the following sections the physical principles of electrostatic precipitation are considered in detail.

LIST OF SYMBOLS

a = effective radius of dust particle assumed spherical (cm).
c = velocity of particle relative to gas ("drift velocity") (cm/sec).
C = kinetic theory r.m.s. velocity of ions (cm/sec).
C_d = drag coefficient.
d = mean density of dust (g/cm^3).
D, D_1, D_2 = diameter of particles (cm).
e = electronic charge (e.s.u.).
E = electric intensity or stress (e.s.u./cm).
F_d = drag on a particle due to flow through the gas (dynes).
g = acceleration due to gravity (cm/sec^2).
i = ionic current leaving unit length of discharge electrode (e.s.u./cm).
k = ionic mobility of negative ions (cm/sec per e.s.u./cm).
k_B = Boltzmann's constant (ergs/deg).
n = number of charges acquired by a particle after a time t sec.
N_0 = ion concentration ($\rho_i = N_0 e$) (ions/cm^3).
$p = \dfrac{3\epsilon}{\epsilon + 2}$.
q = charge on particle (e.s.u.).
Q = limiting charge on particle (e.s.u.).
r = distance of point considered from axis of cylindrical electrode (cm).
R_e = Reynolds number.
R_i, R_0 = effective radii of inner and outer electrodes respectively (cm).
S = total surface area of dust per cm^3 of flue gas (particles assumed spherical) (cm^{-1}).
T = absolute temperature (° K).
U = tensile strength of material (dynes/cm^2).
w = velocity of gas through precipitator (cm/sec).
y = thickness of dust layer (cm).
δ = density of gas (gm/cm^3).
ϵ = permittivity of dust particle.
η = viscosity of gas (poise).
ρ = resistivity (Ω cm).
ρ_i = density of space charge due to ions (e.s.u./cm^3).
τ = charging time constant (sec).

THE CORONA DISCHARGE

The discharge electrode is invariably of negative polarity, since, other things being the same, negative corona gives a somewhat higher current than positive, and the flashover voltage, which limits the operating potential, is appreciably greater.[3,4] Under these conditions, electrons leaving the discharge electrode are accelerated by the intense field in its neighbourhood to a velocity at which they produce positive ions and electrons by collision. The latter are accelerated and produce further ionization, the cumulative process being referred to as an "electron avalanche." Short wavelength radiation, from the excited gas molecules, gives rise to photo-ionization in the surrounding gas and to photo-electrons at the electrode surface which initiate further avalanches. Owing to the high mobility of the electrons (about 10^3 times that of the positive ions) the negative head of the avalanche proceeds rapidly, leaving a trail of positive charge which tends to retard the electrons and, since the field strength decreases rapidly with increasing distance from the electrode surface, the process ceases without a complete sparkover having occurred. As soon as the positive ions have been attracted to the negative electrode the process is repeated. Periodic discharges thus occur at various parts of the electrode surface, and in gases at about atmospheric pressure, take the form of a narrow luminous zone, termed the corona, close to the electrode.

The corona tends to concentrate into "tufts" spaced over the electrode surface, even with smooth cylindrical wires. The discharge is more stable if electrodes producing local high stress concentrations are employed. These commonly take the form of a spiked rod or a twisted wire of about 0·15 in. square cross-section.

The corona process has been studied in detail by Loeb, Meek and others,[5,6,7,8] and the following points are relevant to the study of electrostatic precipitation:

(*a*) Ions are produced principally in the corona region. The ionic current will thus depend primarily on the stress near the conductor surface, which in turn depends on the applied voltage and space charge effects.

(*b*) Once the electrons have slowed to a speed less than that necessary for ionization by collision, that is, have passed beyond the corona, they quickly become attached to molecules, forming negative ions which move towards the positive electrode with a velocity proportional to their mobility and to the electric field. The space outside the corona zone thus carries a negative space charge whose average concentration, under the usual conditions found in practice, is about 5×10^7 ions/cm^3. It is in this zone that the majority of dust particles acquire a negative charge. On the other hand, dust passing inside the corona zone may become positively charged, and be precipitated on the discharge electrode, for there will be a predominance of positive ions in this region because of the high mobility of the electrons.

(*c*) For air the ionic mobility is about 540 cm/sec per e.s.u./cm (1·8 cm/sec per volt/cm). Mobilities are, however, changed considerably by traces of certain impurities in the gas so that the value for a mixture such as flue gas is uncertain.

Under typical operating conditions the mean speed of the negative ions will be of the order 3000 cm/sec (70 m.p.h.).

Back ionization. If the resistivity of the dust layer formed on the collector is very high (above 10^{10} Ω cm), a voltage gradient is built up which causes an electric discharge on the surface of the collector plate. This produces a precipitation process in reverse which seriously reduces the efficiency of the main process. It is possible in principle to reduce the resistance of the dust layer by increasing the temperature to between 300 and 600° F according to circumstance or by increasing the humidity.[9]

Back ionization is not usually troublesome in power station practice, and neither of these artifices is used.

PARTICLE CHARGING

In an electrical discharge two distinct particle-charging mechanisms are present. Firstly, by the bombardment of the particles by ions moving under the influence of the electric field, and secondly, by the attachment of the ions to the particles by ion diffusion.

An exact theoretical treatment would take into account the simultaneous effects of the two mechanisms. This leads to undue mathematical difficulties and, from a practical stand-

point, is unnecessary. Consideration of each mechanism separately indicates that ionic bombardment leads to a charge which is proportional to both the electric field and to the surface area of the particles, and is the process of primary importance in electrostatic precipitation. Charging by ion diffusion does not depend on an external electric field and normally is important only for particles smaller than about 0·2 μ diameter.

Theoretical calculations of particle charging are necessarily based on a number of simplifying assumptions.

1. The particles are assumed to be spherical.
2. Particle spacing is assumed large compared to particle diameter.
3. Ion concentration and electric field in the region of any given particle are assumed uniform.

Assumptions (2) and (3) are closely true in nearly all industrial applications, and assumption (1) is usually a reasonable approximation.

Charging by ion bombardment. The theory of charging by ionic bombardment was first studied by Rohmann[10] and later in more detail by Pauthenier and Moreau-Hanot.[11] The problem is essentially one in electrostatics, and the solution is based on the distortion of the electric field in the neighbourhood of the particle. Ions move along the lines of force and some will strike the particle and transfer their charge. This charge produces a repulsive force which reduces the rate of charging. Ultimately, sufficient charge is received to completely counteract the external field, the electric flux entering the particle being reduced to zero, and charging ceases.

Pauthenier[11] has shown that the charge, q, acquired after t seconds by a spherical particle of radius a and permittivity ϵ in an electric field E_0 is given by

$$q = pE_0a^2\frac{t}{t+\tau} \tag{1}$$

where

$$p = \frac{3\epsilon}{\epsilon+2} \tag{2}$$

The value of p will generally be between 1·5 and 2 for insulating particles, and will be 3 for conducting particles ($\epsilon = \infty$).

The particle-charging time constant, τ, is the time in which half the limiting charge is attained, and is given by

$$\tau = \frac{1}{\pi k\rho_i} \tag{3}$$

where ρ_i is the density of space charge due to ions and k the ionic mobility. The charge reaches 91% of the limiting value in 10τ seconds.

The limiting charge, Q, is given by

$$Q = pE_0a^2 \tag{4}$$

Thus, the limiting charge is seen to be directly proportional to the electric field and to the surface area of the particle, and the charging time constant inversely proportional to both the ion mobility and to the space charge density in the treatment zone.

Formulae for precipitator performance generally ignore the time required for charging as it is assumed to be small compared with the total treatment time, and this is usually true. For instance, in a tubular type precipitator with inner and outer electrodes of 0·15 in. and 5 in. radius respectively, operating at 40 kV with a discharge current of 40 μA per ft, the time to acquire 91% of the limiting charge (that is, 10τ) is found to be about 0·2 sec compared with a total treatment time of about 2 sec. Should, however, the discharge current be reduced to 10 μA per ft, 10τ approaches half the total treatment time.

Charging by ion diffusion. Ions present in a gas share the heat motions of the gas molecules and, in general, obey the laws of kinetic theory. Collisions will therefore take place between the ions and particles in the gas, and provide a charging mechanism which is independent of the externally applied field. The accumulation of electric charge on the particle tends to repel further ions, and progressively decreases the charging rate.

The process has been studied by Arendt and Kallmann[12] and, more recently, by White[13] who gives the following formula for the number of charges, n, acquired after a time t sec,

$$n = \frac{ak_BT}{e^2}\log\left(1+\frac{\pi aCN_0e^2t}{k_BT}\right) \tag{5}$$

where k_B = Boltzmann's constant;
T = absolute temperature;
C = kinetic theory r.m.s. velocity of ions;
N_0 = ion concentration ($\rho_i = N_0e$);
e = electronic charge.

The relative importance of the ion bombardment and ion diffusion mechanisms of charging is illustrated in Table 1, which shows the theoretical number of charges acquired by particles after various periods of exposure to each mechanism. The conditions on which the calculations are based are $T = 300°$ K, $N_0 = 5 \times 10^7$ ions/cm^3, $E_0 = 2$ kV/cm, $p = 1{\cdot}8$ and are representative of a wire in tube assembly, inner and outer radii 0·15 in. and 5 in. respectively, operating in air under atmospheric conditions at 40 kV with a discharge current of 40 μA/ft.

Table 1. *Number of charges acquired by particles*

Particle radius (μ)	Ion bombardment process				Ion diffusion process			
	Period of exposure (sec)				Period of exposure (sec)			
	0·01	0·1	1	∞*	0·01	0·1	1	10
0·1	0·7	2	2·4	2·5	3	7	11	15
1·0	72	200	244	250	70	110	150	190
10	7200	20 000	24 400	25 000	1100	1500	1900	2300

* Limiting charge

It will be seen that the ion diffusion process is predominant for the smallest particles and ion bombardment for the larger.

Fair agreement between observed and theoretical charging rates has been found by several workers[10,11,12,13,14] and, in general, it may be said that charging by ion bombardment predominates for particles larger than about 2 μ diameter, and that the ion diffusion process becomes predominant only for particles smaller than about 0·2 μ diameter. For most industrial applications it is necessary to consider only the ion bombardment charging process.

THE ELECTRIC FIELD AND THE EFFECT OF SPACE CHARGE

Tubular type precipitator. The stress between concentric cylinders due to an applied voltage V_m is given by the equation

$$E = \frac{V_m}{r\log_e(R_0/R_i)} \tag{6}$$

where E is the field at a distance r from the axis, and R_0 and R_i are the radii of the outer and inner electrodes respectively.

When corona occurs, ions transversing the space between electrodes represent a space charge which modifies the distribution of electric stress. Charged particles behave in a similar manner and, owing to their low mobility, the space charge effect due to them is usually considerably greater than that of the ions.

The influence of space charge has been studied by Townsend, Pauthenier, and others, and the following equation may be derived

$$E = \frac{1}{r}\left[\left(\frac{1}{kp^2S^2} + C_0\right)\exp(2pSr) - \frac{2i}{pSk}\left(r + \frac{1}{2pS}\right)\right]^{\frac{1}{2}} \quad (7)$$

where S is the effective total surface area of dust per unit volume of gas, and C_0 a constant of integration which may be evaluated from the condition

$$\int_{R_0}^{R_i} E dr = V_m$$

i.e. the area under the curve of field against distance from the axis is equal to the applied voltage.

When pS is small the equation may be simplified by expanding the exponential term, and becomes

$$E = \sqrt{\left[\frac{2i}{k}\left(1 + \frac{2}{3}pSr\right) + \frac{C_0}{r^2}\right]} \quad (8)$$

or, for zero dust burden

$$E = \sqrt{\left(\frac{2i}{k} + \frac{C_0^2}{r^2}\right)} \quad (9)$$

These equations are often expressed in an approximate form[15,16] by neglecting the term containing C_0 for large values of r, when

$$E = \sqrt{\left(\frac{2i}{k}\right)\left(1 + \frac{1}{3}pSr\right)} \quad (10)$$

and

$$E = \sqrt{\frac{2i}{k}} \quad (11)$$

for zero dust burden.

Curves based on equations (5), (7) and (8) are given in Fig. 1 and show the effect of space charge due to the ions, and due to charged particles, in a tubular type precipitator under typical operating conditions.

It is difficult to calculate the specific surface area of the dust reliably, since it depends critically on the percentage of fine dust. Assuming a typical size grading for fly ash, a dust burden of 18 g/m³ (a moderately high burden) is estimated to have an effective surface area of 0·083 cm² per cm³ of gas and this value has been used in the calculations.

It will be noted that the effect of the space charge due to the ions is to increase the field at the outer conductor and to reduce it near the inner. The effect, however, is small for the discharge currents used in practice. On the other hand, the effect of the charged particles is very considerable, the reduction in stress near the discharge electrode resulting in a reduction in current for a given applied voltage.

Fig. 1 also shows the value of field predicted by the approximate Townsend formula [equation (11)], which is widely quoted. It will be seen that it underestimates the field, even at points near the outer conductor, at the relatively low values of discharge currents which are met with in precipitator practice.

Plate type precipitator. No treatment is available which takes account of space charge effects, but, if these can be neglected, the field between rod and plate electrodes may be calculated, its general form being as shown in Fig. 2.

A particle moving approximately parallel to the plates will pass through a varying electrical intensity, the maximum value being encountered in the plane through the axis of the rod and perpendicular to the plates. In this plane the distribution of field is approximately the same as that between cylindrical electrodes with the diameter of the outer conductor equal to the distance between plates. The particle will thus attain approximately the same limiting charge as for the equivalent cylindrical precipitator, though charging may be somewhat slower since the particle spends most of its time of travel in regions where the field is lower.

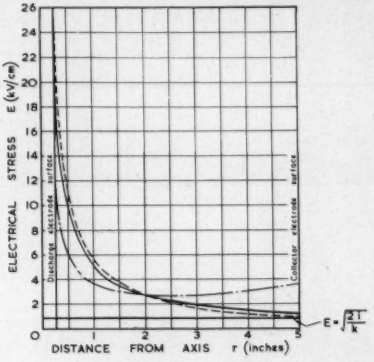

Fig. 1. Field distribution in a tubular type precipitator
– – – – – zero dust burden, zero ionic current.
——— zero dust burden, ionic current 25 μA per foot of discharge electrode.
– – – – – with dust burden, ionic current 25 μA per foot of discharge electrode.
S = dust surface area per cm³ of gas = 0·083 cm⁻¹.
V = 40 kV.

The average value of the outward component of field through which the particle passes is independent of the distance from the centre line, and will be approximately equal to the value at the outer electrode of the equivalent cylindrical precipitator.

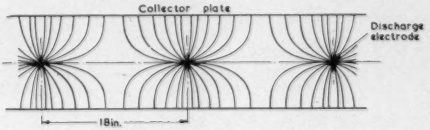

Fig. 2. Field distribution in a parallel plate type precipitator

CALCULATION OF EFFICIENCY

Drift velocity. The drag on a sphere moving through a gas with velocity c is given by

$$F_d = \tfrac{1}{2}\delta c^2 a^2 C_d \quad (12)$$

where δ is the density of the gas and C_d is the drag coefficient, which is a function of Reynolds number R_e for the particle.

For low values of R_e, C_d equals $24/R_e$ and equation (12) reduces to Stoke's law:

$$F_d = 6\pi\eta ac \tag{13}$$

where η = viscosity of the gas (approximately $2{\cdot}4 \times 10^{-4}$ poises for flue gas, according to temperature, etc.), which is accurate for particles larger than $0{\cdot}1\ \mu$ diameter if $R_e \leqslant 0{\cdot}5$. The drift velocity is obtained by equating F_d to the electrical force EQ on the particle, whence, by equation (4),

$$c = \frac{pEE_0}{6\pi\eta}a \tag{14}$$

Values calculated from this equation, and from experimental values of the drag coefficient[17] are shown in Fig. 3 and it will be seen that departure from Stoke's law is only important for large particles at high values of pEE_0. Under typical operating conditions the value of pEE_0 for a particle near the

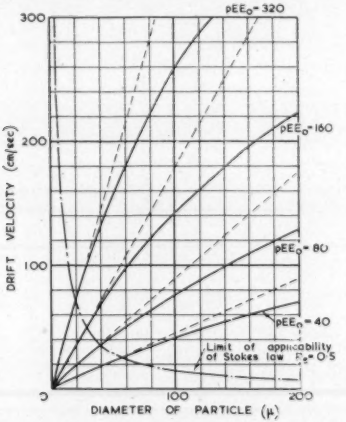

Fig. 3. Variation of drift velocity with particle size

walls of a tubular type precipitator is about 40, and will be correspondingly higher for particles acquiring their limiting charge in the higher fields towards the centre of the tube.

Turbulence and particle size. Particle motion will undoubtedly be influenced by turbulence and electric wind effects in the gas stream. The transverse gas velocity due to turbulence will be about 30 cm per second, i.e. about one-fifth of the mean gas velocity,[18] except near the electrode, and particles between about 15 and 30 μ diameter will have drift velocities of the same order. Turbulence will progressively dominate the motion of smaller particles and be less influential for larger sizes. It may be that electric wind effects increase the aerodynamic turbulence appreciably, but this is not thought likely at the low current densities used.

No treatment has yet been put forward which takes accurate account of these effects. In approximations which have been proposed, turbulence is either neglected[19] or assumed to be the dominant factor in determining the motion of all particles at all parts of the precipitator except close to the collecting electrode, where turbulence progressively decreases and becomes zero in the region of laminar flow. The latter method, due to Deutsch,[20] is generally considered to give results of greater practical value. Its derivation assumes uniform velocity and uniform dust concentration over the cross-section of the tube, and gives the following formula for efficiency of precipitation:

$$\text{Efficiency} = 1 - \exp\left(-\frac{2cL}{R_0 w}\right) \tag{15}$$

where R_0 = radius of the outer electrode;
L = length of the outer electrode;
w = gas velocity.

The variations of efficiency with particle size may be calculated from equations (14) and (15), and the results for typical operating conditions are shown in Fig. 4.

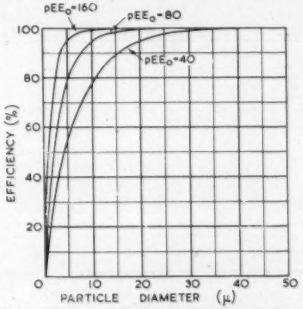

Fig. 4. Variation of precipitation efficiency by Deutsch's formula with particle size

Even allowing for the departure from Stoke's law, large particles should be much more readily precipitated than small ones. This result is not confirmed in practice and the efficiency for large particles is generally found to be of the same order as that for fines, and may be either higher or lower.[21, 22]

In the authors' opinion the cause of the discrepancy lies in effects which occur after the particles have reached the collecting electrodes, and which do not appear to have been considered in detail in the published literature. The effects are considered in the following section which deals in dimensions and orders without attempting to evaluate constants accurately, but which nevertheless helps to reconcile the theory already given with the performance of practical precipitators.

RE-ENTRAINMENT

When the particle reaches the collecting electrode, it is generally assumed that it is held there because it retains its negative charge. This cannot be completely true since, in practice, the ionic current would cause the charge on the dust layer to build up so rapidly that breakdown would occur in a few milliseconds. Hence, if a precipitator is operating without back ionization, the particles must be losing charge by conduction. Moreover, if they did not, the charges would tend to split up the aggregates into separate particles when they were rapped off the electrode.

The particle is, in fact, mainly held by molecular forces of adhesion. If the particles have a high resistance, the ionic current will maintain some negative charge which will provide

an additional force of adhesion. On the other hand, if the particles have a low resistance a positive charge will be induced and this will produce a force tending to remove them. These forces are now examined.

Particle adhesion. C. N. Davies[23] applies some work by Bradley based on wave mechanics and obtains the following results for the force holding a quartz sphere to a quartz plane and the acceleration needed to dislodge it.

Part Diameter (μ)	*Force* (*dyne*)	*Acceleration* (*cm/sec²*)
1	$2{\cdot}1 \times 10^{-2}$	$4{\cdot}05 \times 10^{10}$
100	$2{\cdot}1$	$4{\cdot}05 \times 10^{6}$

While every worker with fine dust knows the tenacity with which small particles adhere to themselves and to surfaces, these values seem too high to be typical. They may be modified by the presence of smaller particles (as will be discussed later) but another approach, which is more convenient, if less rigid, is as follows.

The forces of adhesion are assumed to be molecular forces which become negligible at distances greater than one atomic diameter (10^{-8} cm) and inside this distance they are of the same order as the forces producing the tensile strength of a solid. If two spheres of diameter D_1 and D_2 are in contact, the area where opposing molecules are within a distance of 10^{-8} cm is given by simple geometry as

$$\pi \frac{D_1 D_2}{(D_1 + D_2)} \times 10^{-8}$$

Let U be the tensile strength of the material composing the particles in contact. The force opposing disruption is

$$f = \pi U \frac{D_1 D_2}{(D_1 + D_2)} \times 10^{-8} \qquad (16)$$

In the case of a particle and a plane the formula becomes $\pi UD \times 10^{-8}$. The tensile strength of quartz filaments is 10^{10} dynes/cm² and the density is 2·7. Hence, for a particle touching a plane:

Diameter (μ)	*Force* (*dyne*)	*Acceleration* (*cm/sec²*)
1	3×10^{-2}	2×10^{10}
100	3	2×10^{6}

These results are in good agreement with the results given by C. N. Davies. The greater discrepancy in the end column is due to taking a density of 2·7 while he took density 1.

Taking $U = 10^8$ dyne/cm² as being typical of fly ash particles and 2 as a typical density the figures become:

Diameter (μ)	*Force* (*dyne*)	*Acceleration* (*cm/sec²*)
1	3×10^{-4}	3×10^{8}
100	3×10^{-2}	3×10^{4}

It thus appears that quartz is an extreme rather than a typical substance. The figures still seem unduly high.

If, however, it is assumed that the plane is contaminated with small particles which separate the main sphere from the plane the results for 100 μ spheres become:

Diameter of contaminating particle (μ)	*Force* (*dyne*)	*Acceleration* (*cm/sec²*)
10	3×10^{-3}	3×10^{3}
1	3×10^{-4}	3×10^{2}
0·1	3×10^{-5}	3×10

Thus the assumption that a plane is contaminated with particles of diameter 1 μ, or has roughness with the same radius of curvature, will reconcile the formula with common experience of 100 μ particles. These figures are calculated on the assumption that the 100 μ particles rest on one of the smaller particles. In practice, the effect will be modified because many small particles may lie between the large particle and the plane.

The electric force. As soon as the particle touches the collector plate its negative charge will be reduced by conduction. If the contact resistance is high the ionic current to the particle will maintain some negative charge. Assuming that the contact of a particle with a plane is limited to the area where the gap is less than a certain fixed distance, the area of contact will be proportional to D and the resistance of the contact will be proportional to ρ/D where ρ is the resistivity of the material. The ionic current to the particle will be proportional to $D^2 i$. The voltage built up will therefore be proportional to $D^2 i \times \rho/D = Di\rho$. Considering the region of contact as a small condenser, the charge built up will be proportional to the area of contact and the voltage, i.e. to $D^2 i\rho$. The electric force on this charge will be $C_1 E D^2 i\rho$, where C_1 is a constant. In addition an induced positive charge will tend to build up. The electric force on this charge is given very approximately by

$$\frac{\pi D^2}{4^2} \times \frac{E^2}{8\pi} = \frac{D^2 E^2}{32}$$

The net force on the particle will be an attractive force of

$$C_1 E D^2 i\rho - \frac{D^2 E^2}{32}$$

$$= D^2\left(C_1 E i\rho - \frac{E^2}{32}\right) \qquad (17)$$

If the resistance is high enough the force will be attractive for all particle sizes and there will be no tendency for the particle to leave the collecting electrode. However, as shown above, the voltage across the point of contact is $Di\rho$ and the voltage gradient is proportional to D and hence large particles may be more liable to cause back ionization in highly resistive dusts.

If the resistance is low there will be an electric force tending to remove the particle from the electrode which will be resisted by the molecular force of adhesion. In the case of a particle of negligible resistance the electric force $= D^2E^2/32$. The molecular force is $\pi UD \times 10^{-8}$ dynes and again taking U as 10^8 dynes/cm² is πD. There will be a critical value of D above which the electric force will overcome the molecular force and remove the particle from the electrode. This value is given by $D^2E^2/32 = \pi D$ and taking $E = 12$ (typical for heavy dust burdens), $D = 0{\cdot}7$ cm. If the effect of contaminating small particles is considered, say 1 μ, the molecular force is $\pi \times 10^{-4}$ and $D = 80\,\mu$.

It appears then that in some cases large conducting particles will escape from the collector immediately. Carbon particles (which are usually conducting) are very often spongy in structure. The electric forces are undiminished by this effect, but the molecular forces may well be reduced both by the lower effective density and the fact that the radius of the point of contact may be very small.

Strength and size of dislodged dust aggregates. The formula for the molecular force between particles can also be applied to aggregates of particles. Consider a cross-section of an aggregate composed of particles of uniform size. The number

of particles per unit area is inversely proportional to D^2. The molecular force per contact is proportional to D so that the strength of the material to oppose disruptive effects is inversely proportional to D. Small particles can therefore build up larger aggregates than large ones. In a mixture consisting mainly of large particles but containing some smaller ones, the strength of the aggregate will be further reduced by the presence of small particles at the points of contact.

The thickness of the dust layer which will be dislodged by rapping and the size of the resultant aggregates may also be estimated. The rapping produces an acceleration—say Ng. The thickness of the layer which can be dislodged is given by equating the adhesive force to the disruptive force and is:

$$y = \frac{4U \times 10^{-8}}{D \times d \times Ng} \tag{18}$$

where d is the mean density of the dust layer.

If $U = 10^8$ dyne/cm^2 and $d = 2$

$$y = 2/DNg \tag{19}$$

If $N = 10$ and $D = 20\ \mu$

$$y = 0{\cdot}1 \text{ cm} = 1000\ \mu$$

If contamination by 1 μ particles is assumed

$$y = 50\ \mu$$

Assuming the shear strength of the material is of the same order as the tensile strength, the thickness which will break off under its own weight is $y = 1$ cm and $y = 500\ \mu$ in the two cases for 20 μ particles. For 100 μ particles the figures are 2000 μ and 20 μ respectively. The size of particle which can fall against the main gas stream is about 500 μ. It is therefore important to dislodge the dust as gently as possible, particularly when large particles are concerned.

CONCLUSIONS

Existing theories of electrostatic precipitation do not adequately account for the performance of large scale plant, particularly in the relation between particle size and precipitation efficiency. This paper attempts to extend the theory to the important processes which take place after the particles reach the collecting electrode.

It would appear that all particles with the exception of the very finest are swept to the collector with great efficiency: that all particles are tenaciously held with the exception of the largest, and, of these, highly conducting particles are especially likely to escape: that when an accumulation of fine material breaks off under its own weight or under the action of rapping it will in the main form large aggregates which will fall into the hopper, while if the material is coarse it will form smaller aggregates, some of which may be carried out by the flue gas. While some method of dislodging the dust from the plates is usually essential, the theory indicates that it should be done as infrequently and as gently as possible while ensuring that dust is in fact removed. There is little evidence to show that this has been considered in practical designs.

Theory indicates that the present design of precipitator cannot achieve 100% efficiency since some very small particles may never reach the collecting electrodes, their motion being dominated by turbulence, and since large particles, which are readily brought to the collector plates, are particularly liable to re-entrainment in the gas stream. Overall performance can be improved by prefacing the normal precipitator by a mechanical collector, a practice which is being adopted in some power stations, or by shutting off the gas flow through sections of the precipitator while they are rapped. The present system of simultaneous and continuous electrification and collection is clearly desirable for larger particles since a particle which escapes from the collecting electrode will be recharged and may ultimately be trapped. It is not suitable for the finest particles because the turbulence caused by flow conditions and electric wind completely masks their drift velocities, so that the small particle only arrives by chance in the region near the collecting electrode where precipitation is possible. However, if it is once collected it is strongly held.

Providing that the large particles can be completely removed before the final stage of the precipitator, it would seem that the collection of small particles could be made more efficient by making the final stage one in which stream line flow is maintained. The drift velocities of the small particles would then operate without interference by turbulence. Since the particles would be charged before entering this section there would be no need for ionizing current and this would obviate turbulence due to electric wind and permit higher mean voltage gradients to be employed.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. J. S. Forrest, both for the opportunity to present this paper and for assistance in its preparation; to Mr. J. H. Gosden for the diagrams and for other material; and to Sturtevants Ltd. and Simon-Carves Ltd. for the use of slides showing details of their equipments when the paper was read.

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DISCUSSION

Dr. D. G. Marshall: Does the theory of the precipitator assume the particles arrive uncharged? Is this assumption justified?

Authors' reply: The theory does assume the particles are initially uncharged. On the whole the particles have plenty of time for their charges to approach equilibrium so the effect of the initial charge, if any, is negligible.

Two electrostatic field-meters*†

By A. S. CROSS, M.Sc., Grad.Inst.P., Research Laboratories, Kodak Ltd., Harrow, Middlesex

Two electrostatic field-meters are described, one operating from a.c. mains and the other from dry batteries. An alternating potential proportional to the field is generated by the measuring head, amplified, and fed to a phase-sensitive rectifier. The mains-operated instrument gives, at full sensitivity, an output current of 1 mA for a field of about 400 V/ft, the direction of the current depending upon the sign of the field. Its sensitivity can be adjusted over a range of 900 : 1; at maximum sensitivity the zero drifts by no more than 2% of the full-scale reading in 15 h. The battery-operated instrument, which is truly portable, has two fixed ranges giving full output current for fields of 5 and 50 kV/ft; its sensitivity is hardly affected by normal changes in battery voltages.

The most satisfactory instruments for the measurement of electrostatic fields, based on an electrometer devised by Gunn,[1] have been described by Pinoir,[2] Waddel[3] and Cleveland.[4] In these instruments an insulated electrode is alternately exposed to and shielded from the field by the blades of a rotating metallic sector wheel. An alternating potential is thus generated on the electrode, and is then amplified and rectified for measurement. Mechanical rectification by means of a switch on the sector wheel shaft has been used to discriminate between fields of opposite sign, but is sometimes unreliable and electronic methods are preferable for continuous operation. Simple electronic rectification, however, can only give sign discrimination if the zero is offset.

The first instrument described, which is operated from an a.c. mains supply, differs from these mainly in the method of rectification. The second is powered by dry batteries and is very similar to that described by Waddel,[3] the main difference being the adoption of a miniature form of construction which enables the complete instrument to be truly portable.

THE MAINS-OPERATED INSTRUMENT

This instrument retains the advantages of both of the earlier systems by using a phase-sensitive electronic circuit. Zero signal corresponds to zero field, thus giving good stability and allowing the sensitivity to be changed without zero shift. The rotating sector wheel is driven by a synchronous motor, and a signal frequency double that of the mains frequency gives the simplest possible measuring head and reference signal supply consistent with unique phase relationships.

The measuring head. The construction of the measuring head is shown in Fig. 1. A two-pole synchronous motor,

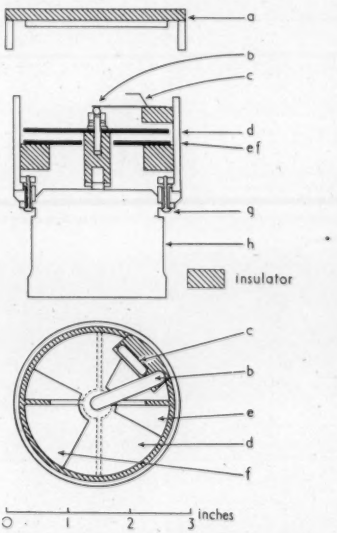

Fig. 1. Mains-operated field-meter measuring head

a, cap; *b*, contact to rotor; *c*, contact to cap; *d*, rotor; *e*, signal stator; *f*, reference stator; *g*, screws for locking phase adjustment; *h*, motor (Evershed and Vignoles Ltd. type FC/34/0).

* Communication No. 1541 H.
† Since the preprint of this paper became available in March 1953 the author has added a description of a second field-meter powered by dry batteries.

operating at 3000 r.p.m., is used to drive a two-bladed rotor which then produces a 100 c/s signal. The four stator plates, consisting of alternate signal and reference stators, are fixed to an insulating ring, through which the cable is led out of the head (under one of the reference stators). The rotor is attached to the motor shaft by means of an insulating bush. In order to adjust the phase of the signal, the motor case can be rotated relative to the stator.

An important consideration is that of possible contact potential differences between the electrodes; because of the small distance between the rotor and the stators a potential difference of 1 V between them produces a signal corresponding to a field of about 200 V/ft. In order to adjust the zero it is therefore necessary to provide means for adjusting the potential of the rotor by a small amount on either side of the stator potential; this has been carried out by connecting the stators to a small fixed positive potential and the rotor to a similar variable one. Changes of the contact potential difference in the slipping connexion to the rotor will cause zero shift, and contact has been made in such a way as to involve the least sliding, through a ball bearing and a leaf spring arranged to contact on the axis of rotation. The electrodes have been made of stainless steel and the connexions of ordinary steel.

The measuring head is supplied with a cap carrying an insulated metal plate. When the cap is in place this plate makes contact with a spring which can be connected to a constant positive potential, and provides a convenient means of checking the overall sensitivity.

The amplifier. The circuit of the amplifier and phase-sensitive detector is shown in Fig. 2. It is based on a similar unit, which has been described by Dighton,[5] and which is used as a standard piece of equipment in these laboratories. The signal is fed into it by a potentiometer (R_2, R_3, R_4, R_5), by means of which the sensitivity may be adjusted in known steps, and is amplified by the valves V_1, V_2 and V_3. The gain of this amplifier is stabilized by negative feedback from the cathode of V_3 to the cathode of V_1; R_{27}, in this negative feedback circuit, provides a continuous sensitivity adjustment. This arrangement usually enables the correct sensitivity to be obtained with the step control in one of the two central positions, so that the sensitivity can be increased or decreased by a known amount if the field changes greatly.

The output of the amplifier is fed *via* the transformer T_1 into the phase-sensitive detector, which is also fed with a 100 c/s reference voltage from a bridge rectifier (U_1, U_2, U_3, U_4) supplied at 50 c/s. In the absence of a signal the condensers C_{11} and C_{12} are equally charged by the detector rectifiers (U_5, U_6, U_7, U_8) and no current flows through the meter; the presence of a signal unbalances this reference

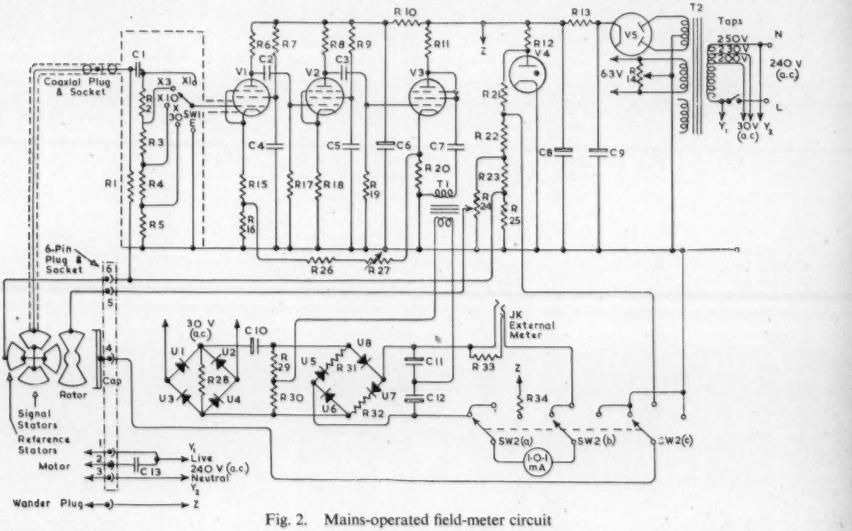

Fig. 2. Mains-operated field-meter circuit

Component values

R_1 = 4·7 MΩ
R_2 = 680 kΩ, 1% high stability
R_3 = 220 kΩ, 1% high stability
R_4 = 68 kΩ, 1% high stability
R_5 = 33 kΩ, 1% high stability
R_6, R_8 = 470 kΩ, ½ W
R_7, R_9 = 2·2 MΩ
R_{10} = 100 kΩ, 2 W
R_{11} = 50 kΩ, 2 W
R_{12} = 33 kΩ, 2 W
R_{13} = 2 kΩ, w.w. 6 W
R_{14} = 250 Ω, w.w. variable
R_{15}, R_{16} = 1·5 kΩ
R_{17} = 100 Ω w.w.
R_{18}, R_{19} = 1 MΩ
R_{20}, R_{23}, R_{25} = 470 Ω w.w.
R_{21} = 15 kΩ, high stability
R_{22} = 10 kΩ, high stability
R_{24} = 5 kΩ w.w. variable
R_{26} = 1 kΩ w.w.
R_{27} = 100 kΩ w.w. variable
R_{28} = 220 Ω w.w.
R_{29}, R_{30} = 330 Ω w.w.
R_{31}, R_{32}, R_{33} = 1 kΩ
R_{34} = 330 kΩ, 5% high stability

All resistors not otherwise specified are ½ W, 20%

C_1–C_5 = 0·1 μF, 500 V d.c., paper
C_6 = 16 μF, 500 V d.c., electrolytic
C_7 = 0·25 μF, 500 V d.c., paper
C_8, C_9 = 8 μF, 500 V d.c., electrolytic
C_{10}, C_{11}, C_{12} = 25 μF, 25 V d.c., electrolytic
C_{13} = 1·25 μF (supplied by motor manufacturer)

U_1, U_2, U_3, U_4 = Westinghouse Type SD23
U_5, U_6, U_7, U_8 = STC Type K2–3

V_1, V_2, V_3 = 6SJ7
V_4 = 85A1
V_5 = 6X5

T_1 = Wearite Hyperloy 209
T_2 = Woden RMS 11 A
350–0–350 V, 80 mA 6·3 V, 3 A
5 V, 2 A

SW_1 = 1-pole, 5-way rotary switch
SW_2 = 3-pole, 3-way rotary switch

JK = Switch jack

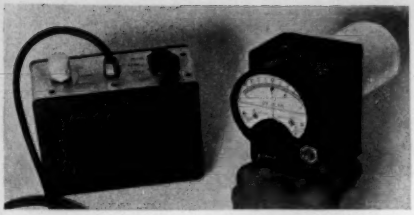

Fig. 3. Portable battery-operated field-meter

supply and thus causes current to flow through the meter. The magnitude of the reference voltage required depends on the resistance of the meter which is used; for a 3000 Ω meter the bridge needs about 24 V while for meters of 1000 Ω or less a 12 V supply is sufficient. In the instrument at present in use the bridge is supplied with 30 V obtained from the primary of the mains transformer, in order that a high-resistance external meter may be used.

The small positive voltage for the stators and rotor is obtained from a stabilized supply through a resistance chain R_{21}, R_{22}, R_{23}, R_{24} and R_{25}, variation of the rotor potential by means of R_{24} providing the zero adjustment. This chain also supplies a stabilized calibrating voltage, which is applied to the cap when required by the switch SW_2. This switch has three positions, providing the following facilities:

1. Normal operation: the cap is earthed for zero setting;
2. Sensitivity check: the cap is connected to the fixed voltage;
3. High tension voltage measurement: this has been provided so that the unstabilized h.t. voltage can be used externally for calibrating a particular experimental arrangement.

The motor is supplied from the mains through the condenser C_{13}.

Performance. The maximum sensitivity gives a full-scale reading of 1 mA for a potential of 400 V on a flat surface 1 ft from the measuring head. It should be noted that this does not necessarily correspond to a field strength of 400 V/ft, as the measuring head distorts the field; the importance of this effect is not generally realized, and field-meters of most types should be calibrated in position by applying a known voltage to a conductor placed in the same position as the surface to be measured. This sensitivity can be reduced to one-thirtieth by the step control and independently, by about the same amount, by the continuous control.

After an initial warming-up period of about 15 min, the zero drifts by no more than 2% for the full-scale reading in 15 h, when running at maximum sensitivity. To obtain such stability the stators and rotor must be perfectly clean. Immediately after cleaning, however, the zero drifts slightly for several hours before reaching its stable position.

THE BATTERY-OPERATED INSTRUMENT

The complete instrument, as shown in Fig. 3, consists of two units connected by a multicore flexible cable, one pistol-like unit containing the measuring head and amplifier, and the other containing the batteries. Rectification is performed by a cam-operated switch on the rotor shaft, the instrument not being intended for prolonged use. It was considered adequate to provide two fixed sensitivities giving full-scale readings corresponding to fields of about 5 and 50 kV/ft.

The measuring head. The signal generator itself is in principle a scaled-down version of that described above, having an outside diameter of 2 in. The rotor and the cam for the rectifying switch are mounted on a shaft running in ball races, which is driven through a short flexible coupling (a coil spring) by an industrial type Micromotor, made by Victory Industries Ltd. No attempt is made to control the motor speed, which is normally between 1500 and 4500 r.p.m. To minimize vibration and improve reliability, the switch consists of two symmetrically arranged units connected in parallel, each having been adjusted to provide satisfactory operation. The rotor potential is controlled by a leaf spring contact bearing on the end of the shaft, conduction through

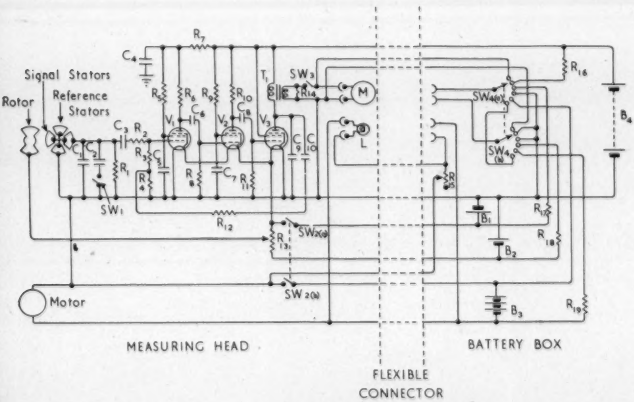

Fig. 4. Battery-operated field-meter circuit

R_1, R_3, R_9 = 10 MΩ
R_2, R_5, R_{12} = 2·2 MΩ
R_4 = 30·8 kΩ*
R_6, R_{10} = 1 MΩ
R_7 = 470 kΩ
R_8 = 3·3 MΩ
R_{11} = 5 MΩ
R_{13} = 500 kΩ variable
R_{14} = 2·2 kΩ
R_{15} = 25 Ω variable
R_{16} = 1·5 MΩ, 2%
R_{17}, R_{18} = 55 kΩ, 2%
R_{19} = 150 kΩ, 2%

All resistors not otherwise specified are 1/10 W, 20%

C_1 = 0·004 μF, 150 V d.c.
C_2 = 0·036 μF, 150 V d.c.*
C_3, C_5–C_{10} = 0·1 μF, 150 V d.c.
C_4 = 0·3 μF, 150 V d.c.

B_1, B_2 = Ever-Ready U.11
B_3 = 2 Ever-Ready 1289 (in parallel)
B_4 = 2 Ever-Ready B.122 (in series)

V_1, V_2 = Hivac XFW 30
V_3 = Hivac XFY 31

T_1 = Wearite Hyperloy 208

L = 2 6 V 0·04 A M.E.S. lamps (in parallel)

SW_1 = Single-pole toggle switch
SW_2 = Double-pole double-action push switch
SW_3 = Cam-operated switch
SW_4 = Two-pole six-way rotary switch

M = 50–0–50 μA meter

* These components are selected to give correct sensitivities.

the ball races having been found unsatisfactory. Earthed steel disks provide screening between the motor, switch and stators.

The amplifier. The circuit of the amplifier is shown in Fig. 4. The time constant of the input circuit C_1, R_1, has been made sufficiently great to prevent the sensitivity changing with motor speed[3] and a second condenser C_1 can be switched in to provide the lower sensitivity range. The use of directly heated valves makes grid current biasing convenient, and the condenser C_3 is used to prevent this bias affecting the zero. Negative feedback from the anode of the output valve to the grid of the input valve, by means of C_{10}, R_{12}, and R_4 stabilizes the gain against fluctuations in battery voltages; R_2 has been inserted into the input circuit to prevent excessive frequency-sensitive attenuation of the negative feedback voltage by the combination of the grid resistor and the input capacity. R_{13} provides zero adjustment, and the battery B_2, which is provided for this purpose only, suffers a constant drain of a few microamperes.

It is frequently necessary to hold the measuring head in a position which does not allow the meter to be read easily. To facilitate use under these circumstances the output meter may be transferred to the battery box, where it may also be used for checking the battery voltages. In either position the meter scale can be illuminated by the lamp L, R_{15} providing a combined switch and brightness control. The whole instrument is switched on and off by a double-pole double-action push switch on the measuring head.

Performance. Correct sensitivity of the instrument on the 5 kV/ft range is obtained by adjusting the value of R_4 in the negative feedback circuit, and the 50 kV/ft range is obtained by choosing the correct value for C_2. With the amount of negative feedback thus determined the sensitivity changes by no more than 2% for simultaneous changes in the battery voltages from 45 to 30 V and 1·5 to 1·1 V. On the high sensitivity range a similar change of sensitivity occurs over the operating range of rotor speeds; on the other range the change is negligible.

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DISCUSSION

Dr. T. B. Rymer: What is the output of the measuring head corresponding to the full-scale reading on the most sensitive range of the amplifier?

Mr. H. Buset: The paper is of great interest because the rotating field meter has not yet come into such a broad use as it deserves. I think it is the one instrument best suited for measurement of static charges in many industries, such as textile, rubber and paper industries. The main advantage in this case is that the meter does not, as ordinary electrometers do, suffer a zero shift as a result of charged dust particles or corona.

I should like to add two references to those given by Mr. Cross. The first is a paper by Helmer Dahl.[1] As far as I know this is the only really exhausting analysis of this subject, and I strongly recommend this paper to anybody intending to build such a meter.

The other paper is that of Mr. Clark, Jnr.,[2] which describes a polarity indicating mechanism. Mr. Cross uses a phase sensitive rectifier, which is possible when using a synchronous motor. If a d.c., or otherwise asynchronous, motor is used, the same can be obtained by arranging a contact on the motor axis, as shown by Mr. Clark.

It is not necessary to employ the moving coil meter for the polarity indication (zero in middle). In Oslo we used a glow discharge tube, and could then have the whole scale for the magnitude indication alone.

Another practical point is to make the calibration of the meter logarithmic, in order to cover a greater range with the same accuracy.

Author's reply: Replying to Dr. Rymer, the output is dependent, of course, upon the detail construction of the head and the capacity of the cable connecting it to the amplifier. For this particular head and about 6 ft of screened microphone cable the figure required is 1·5 mV r.m.s. This is obtained with a field of about 400 V/ft.

I am obliged to Mr. Buset for the two additional references to the literature. Since the preprint was issued a description has been added of a battery-operated instrument which uses a contact controlled by the motor shaft for rectification. The centre-zero meter has been used for polarity indication in order to simplify the use of the instrument, especially when it is unattended and the output is used to operate a pen recorder. For this type of operation a meter with a logarithmic scale would also be valuable, but in the present instrument the complication was not considered worth while.

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Electrostatic coating processes

By R. Tilney, A.M.I.Mech.E., Henry W. Peabody (Industrial) Ltd., Great Suffolk Street, London

This paper describes the three methods of applying static electricity in the production of parts to which it is required to apply liquid coating. Development of these processes has led to their commercial application, in the first case by the introduction of particles of coating material atomized by compressed air into an electrostatic field; in the second case by the removal of surplus coating material from parts coated by dipping; in the third case by direct application of the coating material atomized and deposited by electrostatic force. The principles of these three processes are described and also mechanical and electrical arrangements for their application to commercial production. Finally some details are given of the types of production at present being handled and a summary of the results achieved by way of coating material savings.

Of the various applications of static electricity to industrial problems, that which the Ransburg Company of Indianapolis has developed is the electrostatic deposition of liquid coatings, particularly coatings such as paints and varnishes, to a wide variety of products.

The early development of these processes is a good example of highly technical industrial development following from the posing of a practical problem from the factory. It was in Ransburg's housewares factory, which manufactures large quantities of kitchen and other metal goods, that the idea of applying the principle of electrostatic deposition to paint first arose, when it was determined to reduce the waste of paint occurring as a result of the high percentage of overspray always associated with normal handspray painting methods. From this early work, carried out from 1940 onwards, the three coating processes now available were developed. The following short summary of the principles of each process precedes the more detailed account of each given in the main part of this paper and in both sections the chronological order of development of the processes is taken.

Firstly, the No. 1 process, or air atomized spray process, operates by introducing finely atomized particles of the required coating material from a specially modified type of automatic spray gun operated by compressed air, into an electrostatic field where each particle receives a static charge. Through this same field is passed the work to be coated, the work being loaded on some form of conveyor and through it maintained at earth potential. As a result of the charge on the particles they are attracted to the work at earth potential in accordance with well-known principles and the thickness and uniformity of the coating film are controlled by adjustment of the spray guns and also of the position and method of hanging of the workpieces relative both to the spray guns and to each other.

Next was developed the companion process, electrostatic detearing, applicable to the many types of product which can be satisfactorily coated by complete or partial immersion of the part in a reservoir of the coating material. The process is also applied to products coated by the more recent development of this type of coating method known as "flow coating" in which the coating material is pumped through sprays which do not atomize it but direct it generally at the part to be coated, the excess material draining off the part and being returned to the reservoir.

After both these methods of coating, an electrostatic field can, in properly controlled conditions, be used to remove the final drip or tear remaining on the part after draining is otherwise complete but which adheres to the part in the first place by surface tension and subsequently by the setting of the outer surface of the paint film in the normal course of drying. Such tears naturally spoil the appearance of the finished product and frequently reduce the protective value of the coating, since on complete evaporation of the solvents and subsequent hardening of the film, they become brittle and are easily broken.

Thirdly, the most recent development is the use of an electrostatic field both to atomize the coating material and to deposit it on the workpiece. This process, known as the No. 2 process, represents a complete departure from conventional painting methods and employs static electricity in one of its most spectacular forms.

As in all these processes, the workpieces are at earth potential, but the coating material is fed directly to atomizing heads which are at high potential and therefore charge the paint to that potential by direct contact. These atomizing heads are positioned so that the coating material is projected in a uniform regulated stream on to the workpieces which are passed in front of them; in the process of being so projected along the lines of electrostatic force from atomizing head to workpiece, the material is broken up into extremely fine particles, so fine in fact that they are usually scarcely visible.

The No. 1 process

The original electrostatic spray painting process, using air atomized spray, is now generally referred to as the No. 1 process. The parts to be painted are passed either on an overhead or floor mounted conveyor, which is at earth potential, through an electrostatic field created in a simple type of spray booth, by a cage type of electrode to which a high voltage negative potential of low amperage is applied. This electrode consists of a series of fine wires supported on a light metal frame which is in turn held on insulators mounted on the spray booth. The wires are placed at approximately 8 in. intervals and run at right angles to the direction of conveyor travel and parallel to the vertical plane through this axis of travel. The electrode is so placed that the distance between it and the parts to be painted is approximately half that between it and any other earthed object such as the roof, walls or floor of the spray booth, so that the electrostatic field is concentrated between the electrode and the workpieces.

If the parts to be painted are of particularly uniform size and shape, the electrode is formed to that shape and also to maintain a minimum standard distance between it and the workpieces. This distance is the minimum practical to ensure that the finely atomized spray of coating material which is introduced at low forward velocity between the electrode and the workpiece can be adjusted both in direction and volume to suit the particular parts being coated; this distance also controls the practical electrical potential to which the electrode can be raised.

When the finely atomized particles of coating material reach the electrostatic field they become charged in the ionized air into which the electrons from the corona discharge from the wires of the electrode are concentrated and so tend to move along the lines of electrostatic force set up between the electrode and the workpieces. More precisely, the particles

move along the resultant of the electrostatic force and that due to their forward velocity imparted by the air pressure used to atomize the coating material on leaving the spray gun. The physical forces influencing the particles of coating material immediately before deposition on the article to be coated are, therefore, three in number, firstly the forward velocity from the spray gun, secondly that of the electrostatic field acting generally in a direction at right angles to the first force and thirdly gravitational force. Since it is essential in all painting operations to evacuate the solvent vapours released by atomization of the majority of coating materials, ventilation is provided through the spray booth to counteract, as far as is practical, this gravitational force and thus to maintain the cloud of coating material suspended in the electrostatic field for as long as possible. Ventilation of the booth therefore provides a fourth force influencing the deposition of the coating material.

Ransburg's first contribution to the use of static electricity for commercial painting operations was therefore the working out of methods of combining these forces in order to obtain continuous and consistent results on the production line. In the first place it was necessary, in co-operation with spray gun manufacturers, to obtain a gun which would provide the required fineness of atomization with the lowest possible forward velocity of the atomized material. Secondly, the coating material required modification, firstly so that it could be more easily atomized, that is at lower air pressures giving lower forward velocities, and secondly so that its rate of drying could be reduced. This requirement arose when it was found that greatly improved results could be obtained by spraying along the line of the workpieces on the conveyor rather than at right angles to the line of the conveyor as in normal hand spraying and as was done in Ransburg's original experiments. By spraying along the conveyor two advantages arose: in the first place the spray remained in the electrostatic field longer than by the original method, and secondly the paint film was built up gradually on each workpiece from the point at which it entered the influence of the field until it passed the spray gun, normally a distance of 5 or 6 ft. During this time the initial flash off of solvent could occur, thereby avoiding the excessive trapping of solvent which would occur if a thick film is built up rapidly with coating materials thinned sufficiently to meet the overall conditions imposed by the method.

This arrangement was also much preferable to that whereby the workpiece was sprayed for the 18 in. or 2 ft distance covered by the spray width at right angles to the gun, particularly as any paint passing the workpiece must be lost since there are not, as in the alternative arrangement, workpieces following on which will attract the charged overspray from the first piece. This slowing of the paint solvents is, however, a somewhat undesirable feature of the process since an increased quantity of liquid coating material has to be handled and a slightly longer flash-off time is required between application of the coating and its subsequent stoving. Fortunately, the most recent development, the No. 2 process, in addition to many other advantages, eliminates this adverse feature of the No. 1 process.

Other features of practical importance, introduced into the process, may be summarized as follows:

(*a*) The change from the original electrode used which consisted of a series of points to the present arrangement of fine wires, was made to reduce the amount of coating material attracted to the electrode rather than to the workpiece, as the bulk of metal used in the electrode could be reduced in the new type electrode in comparison to that required for the point construction. Such coating material caused defects on the work when it built up to a point where dried flakes detached themselves from the electrode and were attracted back on to the wet surface of the workpieces in the field.

The change also made for an electrode that could be more easily cleaned and repaired and which was of smaller electrical capacity, thereby providing greater safety in the electrical system since less energy was required to give the necessary field strength and also since the high voltage fell away more rapidly when the transformer was switched off.

(*b*) The spray guns were mounted on reciprocating or oscillating mountings, where this was appropriate, to provide improved distribution of the spray relative to the workpiece.

(*c*) Ventilation of the booth, which might in theory be best arranged vertically upwards through the field to counteract directly the force of gravity, was found to be most generally efficacious if provided in a horizontally or slightly rising plane from front to back of the field and in a direction parallel to the conveyor travel. If the ventilation were arranged vertically, the air velocity becomes critical in relation to variations in many factors which change with each application of the process such as rate of paint emission, atomizing air pressure, and the specific gravity of the paint in use. On the other hand, it was found that with horizontal ventilation the air velocity could be made reasonably standard for all applications.

Returning to the electrostatic operation of the process, it will be readily appreciated that not all types of object can be equally well coated by the method since many parts have interior surfaces where paint coverage is equally important to that of the external surfaces.

These interior surfaces will, of course, be shielded to a greater or lesser extent from the effect of the electrostatic field, but much can be done by careful gun positioning so as to use the initial forward spray velocity of the gun to penetrate and coat the interior surfaces while allowing the overspray from this operation to be deposited further back in the electrostatic field. In the case of many parts, however, electrically shielded areas exist which cannot be treated except as a separate operation either of hand or automatic spraying, either of which can be carried out on the same conveyor line before or after the electrostatic spraying operation.

THE ELECTROSTATIC DETEARING PROCESS

Frequently, parts which are of such a form that electrostatic spraying is not applicable, because their shape provides a high proportion of electrically shielded areas, can be best treated by dipping or flow coating followed by the electrostatic detearing process. This process is applied to remove the final drips or tears of coating material adhering to such parts after they have been dipped or flow coated, and represents a reversal of the operating features of the No. 1 process. This is brought about by arranging for the workpieces to be hung while the excess coating material applied in the first place drains off, in such a manner that the final drip or tear is formed around a relatively acute point.

The parts are then passed on a conveyor through which they are earthed, over an electrode at high potential (usually termed a grid to distinguish it from the electrode used in the No. 1 process) which is constructed of heavy gauge wire mesh (see Fig. 1). In consequence, the discharge points in the electrostatic field set up between the workpieces and the grid are the acute points at which the drips of excess coating material have been formed and this excess coating material is drawn off the drain point on to the charged grid.

The process is simple in principle, but the following points connected with its operation may be noted:—

(*a*) The point at which the workpiece is brought into the

influence of the electrostatic field is controlled by the drain time required for the particular part and the appropriate coating material condition. It must be at such a stage in draining that the last drip has been formed, but has only hardened to an extent when, on its removal, the remaining coating will reflow to form a perfect film.

(*b*) In some instances different parts of the same workpiece will require different drain times so that detearing is often continued over a period of time to meet both requirements; alternatively separate grids can be arranged at appropriate distances along the conveyor line.

(*c*) Grids are sometimes made to conform to the shape of the workpiece as all drain points should be passed at a uniform distance from the grid to obtain the best results.

(*d*) The drain time is normally provided for by varying the length and speed of the conveyor on which the parts are hung, and this conveyor may serve only as a transporter after the parts have been dipped by hand or may be incorporated into a fully mechanized dipping installation.

THE NO. 2 PROCESS

The latest development by Ransburg in the field of electrostatic coating represents a fundamental departure from all previous methods of applying coating materials to any surface.

The No. 2 process operates on the principle of feeding a controlled uniform supply of coating material to a point at which a highly concentrated electrostatic field is formed, the coating material having already been charged to the same high potential as the electrical source producing the electrostatic field. The electrostatic discharge not only breaks up the coating material into considerably finer particles than can be achieved by other means, but also carries it across the intervening air gap in which the field is created and deposits it on the nearest earthed object.

A source of high voltage, low amperage, unidirectional, current is applied to one or more atomizing bells which are in the form of bowls having a sharp edge and an axial feed hole by which coating material can be fed to the inside surface. Mechanical arrangements are provided which ensure that the bells rotate at such a speed that a uniform film of coating material is spread over the inside surface of the bell and is fed at a controlled rate over this surface to the sharp front edge of the bell. The actual rate of flow of material is controlled to suit the area of surface to be coated per minute. The workpieces are passed in front of each bell and generally at right angles to the axis about which the bells turn, and thereby provide the earthed object on which the coating material will be deposited from the bell. This arrangement brings the point of atomization to a position which is comparable with the requirements of normal hand spraying, a point already mentioned when discussing the modifications of coating material properties required for the No. 1 process.

The schematic diagram, Fig. 2, shows the principle of operation of the process as arranged for one single atomizing head. The strong charge applied to the coating material ensures that all of it is deposited on the work, so that the necessary ventilation is limited to that required to remove the solvent vapour. The quantity of air evacuated is therefore very small and has no effective influence on the spray movement. The spray is therefore deposited under the influence of two forces only, firstly the electrostatic force between bell and workpiece and secondly the centrifugal force due to the rotation of the bell. This latter is relatively of much less importance but has the effect of slightly enlarging the pattern provided from a given bell diameter. The balance between these two forces and the resultant spread is controlled by the condition and nature of

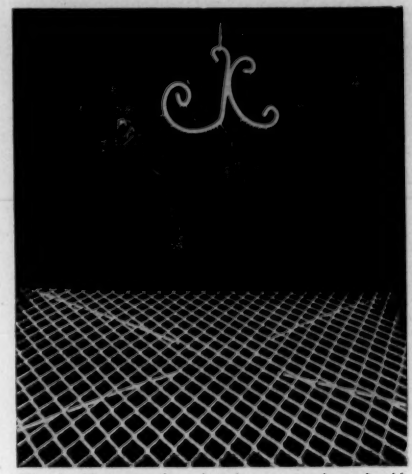


Fig. 1. Demonstration piece hung over charged grid with excess paint being removed by detearing process

the coating material. The viscosity at which the material is sprayed must be accurately controlled if consistent results are to be obtained; the constituents of the paint and solvents have a bearing on whether, in practice, the material atomizes well (that is, whether it is more or less influenced by electrostatic force). Considerable research remains to be done in this field before the reasons for variation between materials are fully understood.

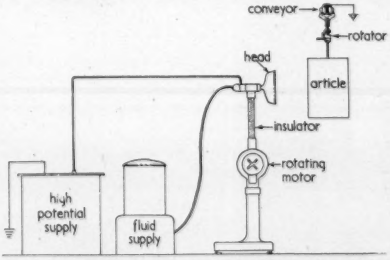


Fig. 2. Schematic diagram showing principle of operation of No. 2 process arranged for one single atomizing head

Similar limitations exist as with the No. 1 process in the matter of electrically shielded areas, and other means may be required to coat these satisfactorily. The process shows such advantages, however, in respect of uniformity and quality of coating, owing to the precise control of the extremely fine atomization and deposition, that these limitations can usually be overcome, and substantial economies and improvement in quality obtained.

EQUIPMENT

For present purposes the most important part of the specialized equipment required for these processes is, without

doubt, the source of high voltage supply since the spray guns, in process No. 1, and the atomizing bells, in process No. 2, together with their mountings, are matters of straightforward mechanical design. The electrical equipment for all these processes is the same and consists of a high voltage transformer combined with a full wave rectifier either of valve or metallic type. The output of this transformer is about 100 kV as a maximum and it is supplied from a 1 : 1 ratio constant voltage transformer. The whole supply is controlled through a spark guard consisting of a balanced electronic circuit whereby the primary current of the transformer is instantaneously cut off if the current in the secondary rises above a pre-determined value, in practice about 2 mA. Risk of sparks from the electrodes or atomizing bells is therefore eliminated. The negative end of the transformer secondary winding is used as the high voltage side, while the positive end of the winding is earthed.

In addition to the sparkguard already mentioned, the supply to the high voltage transformer primary is interlocked with the ventilation and conveyor systems so that if either ceases to operate the h.v. supply is immediately cut off. This, in the No. 2 process, is further interlocked to stop the rotation of the atomizing heads and also of the paint supply pumps, while in the No. 1 process, failure of the ventilation cuts off the paint supply to the guns. Similarly, failure of the ventilation of the detearing grid cuts off the h.v. supply. All these precautions ensure that no inflammable concentration of solvent vapours can accumulate near to any high voltage discharge points and so reinforce the safety provided by the spark guard device.

Other equipment of a specialized nature can be summarized as follows:

No. 1 process

Spray guns. Special air caps and nozzles fitted to standard automatic guns.

Controls. The atomizing air supply to the guns and the coating material supply pressure are both supplied through specially sensitive control valves.

Detearing process.

Specialized electrical control equipment only is required in addition to normal diptanks, conveyors, etc.

No. 2 process

The whole of the spraying equipment is of a relatively specialized nature, but presents no features not encountered in normal mechanical equipment except for the necessity of separating earthed parts such as electric motors from those at high voltage by insulators of suitable length to avoid high voltage tracking.

APPLICATIONS OF THE PROCESSES IN U.K. AND EUROPE

The following examples, taken from the many plants now operating, are mentioned to indicate the versatility of these methods of application of coating materials.

Motor cars. Plants have been installed in which motor car wheels are painted and which have shown savings of over 50% compared with hand spray usage of paint. In this case, automatic spraying of the air slots was necessary as these produce a completely shielded area.

Motor car chassis are also given a complete coating of protective paint after assembly and immediately before completion by final assembly with the body work. The spraying time for this operation may be as low as 2½ min.

Steel tubes. Welded steel tubes are coated externally with rust preventive oil or stoving varnish, at speeds up to 300 ft/min with similar savings of coating material to those shown on the motor car wheel plants.

Tubular steel chairs are also treated; it has been found that the No. 2 process gives satisfactory cover in the partially shielded areas at the welded angle joints whereas the No. 1 process does not. In addition substantial further overall paint economies are provided by the No. 2 process.

Polished plated goods. The uniformity of coating, and also its consistency, have proved valuable in the application of clear or tinted varnishes over polished plated metal goods such as metal pen and pencil tops, etc.

Wooden articles. The normal moisture content of wood provides sufficient conductivity to enable a variety of wooden articles to be satisfactorily sprayed, one of the most spectacular examples being that of coloured and clear lacquer on tennis rackets.

Bicycles and motor cycles. The No. 2 process has shown great advances in painting bicycles, and several plants are in course of construction in Europe, where the decorative colourings applied in bicycle finishing are of extremely high quality.

CONCLUSION

It is hoped that this very limited list of applications will show the variety of industrial uses to which the Ransburg processes can bring the use of static electricity, but the field is continually widening as new methods of application are found successful.

DISCUSSION

Dr. A. J. Maddock: I am interested in the detearing photograph of Fig. 2 from the point of view of possible technical application to the plotting of lines of force. As the field in this diagram is mainly vertical the effect of gravity would be small and so the paint follows the lines of force reasonably well. In the photograph some of the lines cross; is this due to the paint tears coming off one behind the other for the particular object shown or was it that the streams followed in point of time during the exposure of the photograph? With limited electrodes, in place of the large area grid, it seems that this might form a possible method of plotting lines of force for a system.

Mr. D. Bulgin: The process described uses rectified a.c. without smoothing, so that the mean field strength is less and the peak voltage higher than would result with a d.c. supply from an electrostatic generator. Consequently the average forces on a particle or during detearing are less than could be attained. Is this of noticeable practical importance?

Author's reply: Dr. Maddock is correct in assuming that the apparent crossing of the lines of force illustrated by the detearing photograph results from paint tears coming off one behind the other. This could, of course, be shown to some extent in a stereoscopic photograph. Probably the effect is increased in this photograph by the length of time of exposure.

In reply to Mr. Bulgin: Up to the present time it has been found that the reliability of a high voltage supply derived from a transformer with built-in rectifier has been found to outweigh the theoretical advantage of a pure d.c. supply from an electrostatic generator.

The measurement of oxidation of coal by static electrification

By D. G. A. Thomas, M.A., A.Inst.P., Central Research Establishment, National Coal Board, Cheltenham, Glos.

The electrostatic charge acquired by a stream of fine coal particles after making contact with a metal surface has been found to be related to the degree of oxidation of the coal. The effect forms the basis of an instrument for quality control in an oxidation plant.

The oxidation of coal is of considerable interest as a means of modifying the physical and chemical properties of the coal. In particular, the caking of the coal on carbonization may be reduced or prevented by oxidation treatment. The degree of oxidation is important, about 1% of oxygen being adsorbed on, or combined with, the coal. It may be estimated by chemical analysis or trial carbonization, but for the control of oxidation plant, a more rapid indication is required of any departure from the correct operating conditions. The electrostatic charge acquired by the coal when it touches a metal surface is proposed for this purpose.

When a small quantity of fine coal was allowed to slide down an inclined, earthed metal plate, and thence into a box connected to a Farmer electrometer, the coal was observed to have acquired a measurable charge. With raw coal this charge was positive, and with strongly oxidized coal it was negative, intermediate degrees of oxidation giving intermediate values of charge. The effect was reproducible for coal of a given type, particle size range, and quantity.

In order to provide a continuous indication, the instrument must operate on a constant feed of coal. The electrification is then conveniently measured as a current, and a suitable d.c. amplifier used rather than an electrometer. The charging device must be suitable for handling the flow of coal reliably, and the arrangement is shown in Fig. 1. Coal from the hopper *A* is fed at 15 g/min by the constant feed device *B* into the charging device *C*. The latter consists of a metal

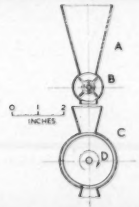


Fig. 1. Charging apparatus

drum *D* rotating at 3000 r.p.m. inside a metal housing, and in passing it the coal makes a number of impacts on the drum and housing. The rotation of the drum produces a steady flow of air through the device which ensures the satisfactory intake and discharge of fine particles having very low free-falling speeds. The charging device is insulated from earth by means of polished polystyrene bushes and the current flowing to it (of the order 10^{-8} A) is measured. Consistent results are obtained with coal of a given type and size range, provided that the mechanical design is such as to prevent any deposit of coal dust building up on the metal surfaces to which the coal is exposed.

The d.c. amplifier is of a type in which the input current develops a voltage across a resistor of a few hundred megohms arranged in a negative feedback circuit. The voltage developed is large (1 to 10 V) and the troubles due to zero drift normally associated with d.c. amplifiers are thereby eliminated. Non-hygroscopic plastic insulators are used throughout to maintain the required insulation resistance.

Fig. 2 is a calibration curve of the apparatus taken with Betteshanger coal (Kent coalfield) oxidized in air at 350° C. The coal sample was crushed before oxidation to pass through a 30 mesh B.S.S. sieve. It must be emphasized that the curve only applies under the conditions specified, although

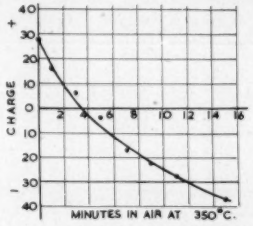


Fig. 2. Calibration of the apparatus

25 units of charge = 10^{-8} coulomb/gram of coal.

similar results are obtained with coals of different type and size. The fact that the curve crosses the zero charge axis, at approximately the oxygen content required, is likely to contribute materially to the reliability of the equipment.

In the hope of simplifying the apparatus attempts were made to transport the coal in an air stream through a tube forming the charging device. It was found that the charge per gram of coal was increased by a considerable factor, depending on the air flow and the geometry of the arrangement, but the results were less reproducible than with the rotary charger. It was found that increasing the air flow, presumably resulting in more violent impacts, tended to give a curve in which the change in the sign of the charge took place at higher values of oxygen content, if at all, perhaps indicating that the attrition was exposing raw or less strongly oxidized coal surfaces.

It has not proved possible to obtain any information on the mechanism of the electrification by the study of the charging of a stream of coal particles, but work is in progress in measuring the charge transfer with a single well-controlled contact between spheres. The resistivity of the coal is of the order $10^9\ \Omega$ cm and increases with increasing temperature.

ACKNOWLEDGEMENTS

The possibility of using an electrical method for this measurement was suggested by Mr. W. H. Walton. Dr. B. G. Knowles also gave valuable help and advice. Thanks are due to the National Coal Board for permission to publish this note. The views expressed are those of the author and not necessarily those of the Board.

Survey of electrostatic generators

By E. S. SHIRE, M.A., Cavendish Laboratory, Cambridge

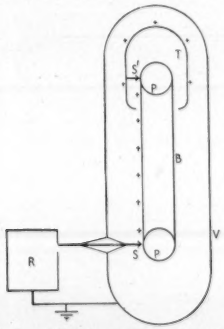
The principles and practical points important in the design of an efficient high-voltage electrostatic generator are described. The special features required for their use in nuclear physics, for X-ray production in medicine and industry, and for sterilization of food and chemicals are considered.

This short survey will be confined entirely to belt machines of the type invented by Van de Graaff[1] for voltages from about half a million volts upwards. Highly efficient machines for lower voltages are described in the contribution by Professor Felici in this Supplement.[2] Only a few of the many variations in the details of practical machines will be mentioned.

PRINCIPLE AND DESIGN

Any account of electrostatic generators must pay tribute to the courage and resource of Van de Graaff and his associates, who have replaced the production of high voltages by such erratic electrostatic equipment as the Wimshurst machine by the highly efficient and reliable belt generators of today.

The principle of the Van de Graaff generator is simple. Charge is sprayed on to a moving belt, *B* (Fig. 1), by a corona



(Reproduced from *The Acceleration of Particles to High Energies*)

Fig. 1. Schematic diagram of generator

T, high-voltage terminal; *PP*, pulleys; *SS'*, points producing corona discharge; *R*, rectifier unit; *V*, containing vessel.

discharge from a row of sharp points, *S*, and removed by a second row of points, *S'*, inside the insulated high voltage terminal, *T*. The voltage builds up until under normal working conditions a steady state is reached when the current carried upwards by the belt is just equal to the useful current and the corona or other leakage from the high-voltage terminal. In practice the corona discharge from the lower points, *S*, requires a potential difference of 10–100 kV, which is usually supplied by a rectifier set, *R*.

Early machines made by Van de Graaff, Tuve and others were unenclosed and used air as the insulating gas. With machines of practicable dimensions much trouble arose from leakage due to the normal humidity of the air or to excessive corona, and from spark-over at voltages over 1 MV. A very substantial improvement occurred when machines were enclosed in relatively small vessels in which the insulating material was gas under pressure. (In principle, adequate insulation should be attained if the machine were surrounded by a vacuum, but in practice it is not possible to obtain a good enough vacuum and there would be many technical difficulties such as arise in spraying charge on to, or removing it from, the belt.) Both maximum voltage and maximum current attainable increase with increasing pressure, at first linearly and then more slowly. In practice air is not used because of the fire risk—at a pressure of 20 atm the partial pressure of oxygen is 4 atm. Commercially pure nitrogen ($\frac{1}{4}$ to $\frac{1}{2}$% of oxygen) is nearly as good as air but strongly electro-negative gases are better. Freon, CCl_2F_2, for instance, is more than twice as good as air at the same pressure and even a small amount added to nitrogen produces a marked improvement. It has, however, two disadvantages: it liquefies at too low a pressure, so that the maximum electrical strength is limited and it disintegrates in the corona from the spray points to produce corrosive compounds. It has, however, been used, in this country, mixed with nitrogen, in at least two machines, the metal parts of which were cadmium plated or varnished. In the U.S.A. it is more usual to use a mixture of carbon dioxide and nitrogen which, though not as good an insulator as nitrogen plus freon, is better than nitrogen alone. Sulphur hexafluoride is considerably better than freon and does not liquefy as easily. Unfortunately it is very expensive and the filling of a large generator would cost £1000 or more.

While the main difference between early and modern machines is the use of high-pressure gas for the insulating medium, there are a number of other improvements mainly intended to keep field stresses as uniform as possible, so as to prevent premature breakdown of a few overstressed parts of the machine. For instance, the space between the high voltage terminal and the containing vessel is usually divided by one, sometimes two, intershields, *I* (Fig. 2), held at potentials which keep the fields at the outer surfaces of the high-voltage terminal, *T*, and the intershields equal. Similarly the voltage gradient down the insulating column, *A*, supporting the high-voltage terminal is sub-divided by a number of metal plates, which are held at suitable potentials by resistances (each several hundred megohms) between the plates.

Fig. 2 shows the design of the generator at Cambridge and Figs. 3 and 4 details of the insulating column and belt arrangement. In this machine the belt is about 16 in. wide and runs at about 4000 ft/sec. It is made of rubber-impregnated cotton, but many other insulating materials can be used with success. In this machine the belt is charged by a corona discharge from spray points, but it is worth noting that

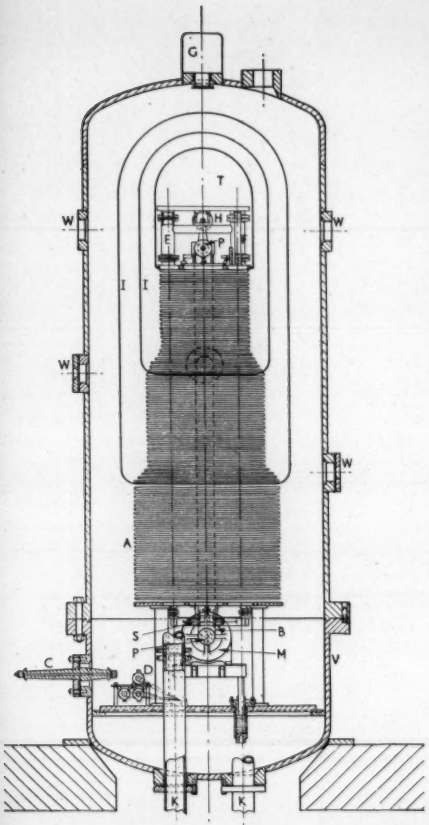


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Fig. 2. Sectional drawing of generator at the Cavendish Laboratory

A, stack of horizontal plates (separating insulators not shown); *B*, belt; *C*, insulated lead supplying voltage for spraying current on to belt; *D*, Selsyn motors controlling ion source in top terminal through glass cords; *E*, *F*, top of accelerating and pumping tubes; *G*, generating voltmeter; *H*, 1000 c/s generator providing power for ion source; *I*, intermediate electrodes; *K*, tubes leading to vacuum pumps; *M*, motor driving belt; *S*, points spraying charge on to belt; *T*, high-voltage terminal; *V*, steel containing vessel; *W*, glass windows.

Professor Trump of the Massachusetts Institute of Technology is obtaining some success by using a belt with a semi-conducting inner surface which is charged by induction as it leaves the bottom pulley in the field of a neighbouring electrode held at a suitable negative potential. The difficulty

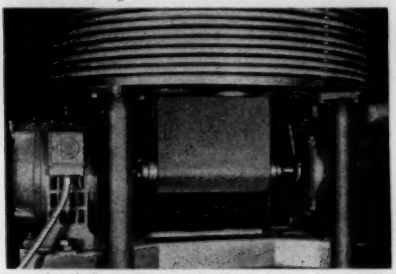

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Fig. 3. Bottom of insulating column, showing belt and driving motors of the Cavendish Laboratory electrostatic generator

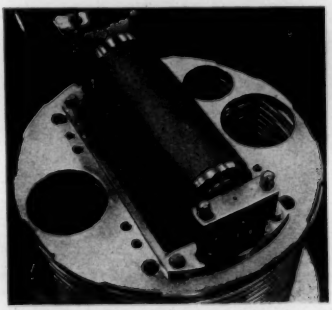

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Fig. 4. Top of the Cavendish Laboratory electrostatic generator stack before addition of ion source or accelerating tubes

with the method is to obtain a semi-conductor of a consistent and suitable resistance. The belt is driven by two 15 h.p. motors directly coupled to the bottom pulley which provide ample power even at the highest pressure, 400 lb/in.^{2}, used. Most of the power is, of course, used in overcoming air friction.

It is not practicable to bring the high voltage outside the machine, so that electrons or other particles are accelerated down evacuated tubes placed inside the machine. Surrounded by the insulating column, a uniform gradient is maintained down the tubes, a matter of importance in obtaining a high total voltage across the tubes. Two such tubes are often, though not always, used for machines accelerating protons or other nuclei. It is then possible to use differential pumping, so that the protons are accelerated

in a higher vacuum than would be possible if only one tube of the same size were used. The production of secondary electrons by the heavily ionizing protons is thus kept small and the loading of the machine by back-streaming electrons and other unwanted effects minimized. In most machines, and until recently, the limit to the maximum usable voltage of a machine was set by the acceleration tubes, but the recent design of the High Voltage Engineering Corporation of the U.S.A. is sufficiently effective to suggest that further attention to the design of the voltage-producing parts might be worth while. A number of features are believed to contribute to the success of tubes, though the phenomena leading to, and occurring at, break-down are far from being clearly understood. The tubes must be sub-divided and the High Voltage Engineering Corporation use glass rings 1 in. long, 6 in. diameter (see Fig. 5), separated by metal electrodes each

(By permission of Corning Glass Works)

Fig. 5. Constructing an acceleration tube

connected to the adjacent plate sub-dividing the column supporting the high-voltage terminal. The electrodes are dished to protect the glass from bombardment by particles traversing the tube and to prevent deflexion of the beam by charges which build up on the glass. The holes in the electrodes are made progressively larger towards the ends of the tubes from a minimum size at or near the negative ends of the tubes. The reverse electron current is then very small, presumably because repeated secondary-electron multiplication at the electrodes is prevented. Unless very efficient baffles are employed reverse electron current can be troublesome if oil vapour-pumps are used. Mercury pumps used with liquid air or solid carbon dioxide traps do not give rise to this trouble. The maximum voltage which a tube can sustain increases with the length of the tube, but is not, unfortunately, proportional to the length of the tube, but only to about the three-quarters power of the length. The best performances reported so far are 6·5 MeV on a tube 12 ft long and a little over 8 MeV on a tube 18 ft long. Under these conditions each 1 in. section of the tube is, on the average, withstanding 45–50 kV, whereas a single section will withstand 70 kV or more, so that there is still room for improvement in the tube as a whole.

MACHINES FOR SPECIAL PURPOSES

1. *Machines for nuclear physics.* The special requirements here are: (*a*) a high voltage, easily varied and under accurate control; (*b*) a moderate beam of 1–50 μA of protons, deuterons, and helium ions; (*c*) a very small spread of energy of the particles in the beam; (*d*) a good focus giving a beam not more than a few millimetres in diameter.

Fig. 6 shows diagrammatically a typical installation and Figs. 7(*a*), 7(*b*) a large accelerator. The double magnet, *F*,

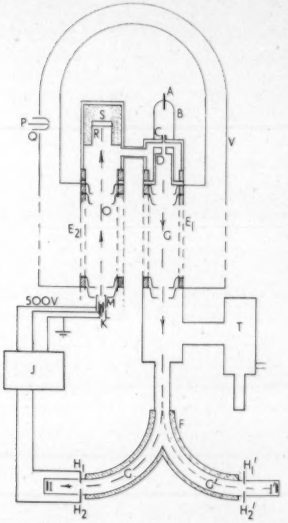

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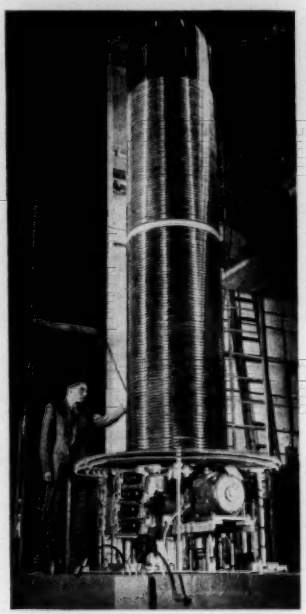
Fig. 6. Typical arrangement for nuclear physics research

A, ion source anode; *B*, glass bulb; *C*, cathode; *D*, focusing electrode; E_1, E_2 acceleration tubes; *F*, polepieces of magnet for separating wanted from unwanted ions; *G*, ion beam; H_1, H_2, electrodes detecting displacement of ion beam from standard path; *I*, target; (G', H_1', H_2', I', similarly for alternative experiment when field of magnet is reversed); *J*, amplifier; *K*, *L*, *M*, cathode, control grid and anode of gun providing electron beam, *O*, which acts as an artificial load; *P*, *Q*, electrodes for alternative method using controlled corona discharge for producing artificial load; *R*, aluminium target for electron beam; *S*, lead shielding; *T*, mercury pump and liquid air trap; (Pump connected to second acceleration tube not shown.) *V*, vessel containing generator.

used to separate wanted from unwanted ions, is very convenient in that it permits a quick change from one experiment to another with different apparatus by reversing the magnetic field. The generator can thus conveniently be used for 16 hours a day or more and one experiment can be prepared while another is being carried out.

A homogeneous ion beam can be obtained by starting with an inhomogeneous beam and analysing it by a magnet fitted with fine slits, but this is obviously wasteful. A better method is to use an ion source giving ions with a small energy spread and to control the accelerating voltage within narrowly spaced limits. A very convenient ion source is that due to Thonemann and others,[3] in which power of 100 W or more, at a frequency of 10 mc/s, or more, is used to produce intense ionization of *atomic* hydrogen or helium within the

glass bulb, *B* (Fig. 6). Ions are extracted from the plasma by applying a few kilovolts to the electrode, *A*. A dark space forms near the cathode, *C*, and practically the whole voltage drop occurs across this, so that ions emerge with only a small energy spread. After leaving the cathode the ions are further



(By permission of High Voltage Engineering Corporation)
Fig. 7(*a*). 5·5 MeV accelerator for positive ions. 100 μA total ion beam

accelerated by the electrode *D* and the main accelerating voltage of the machine. By adjusting the voltage of the electrode *D* the beam can be brought to a focus at any convenient point beyond the end of the acceleration tube.

In practice, if the current sprayed on to the belt is suitably stabilized, the voltage of a machine fluctuates by $\pm\frac{1}{4}$ to $\pm\frac{1}{2}\%$; say 20 kV for a 2 MeV machine. This is too much for many experiments in nuclear physics, so that the voltage of the machine must be further controlled to reduce these fluctuations. These arise from slight irregularities in the belt and its movement and slight changes in ion or leakage current. The fluctuations have frequency components from a few cycles per second from belt irregularities to quite high frequencies from minor discharges in the acceleration tube or from the ion source. In addition there is a tendency to slow drift. Some idea of the problems involved can be obtained if we assume that the current drawn from the machine can change suddenly by 10 μA. The capacity of the high-voltage terminal is about 100 $\mu\mu$F so that the voltage will change by 100 kV per second. If the voltage is to be held constant to 1 kV a correction system must act in a few milliseconds and so must work from zero frequency, to control slow drifts, to a few kilocycles per second. The capacity of the high-voltage terminal is sufficient to smooth out any higher frequency components which arise from

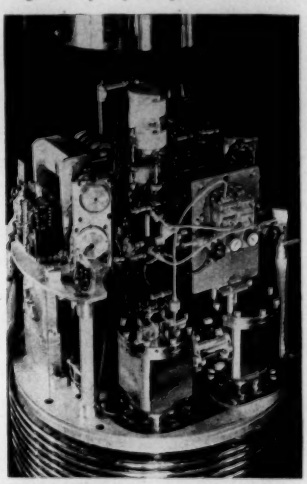


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Fig. 7(*b*). Interior of high-voltage terminal

changes of current of a few microamps. To obtain effective control the voltage must be determined in terms of some reliable standard and this may be done by measuring the bending of the ion beam in the (stabilized) magnetic field

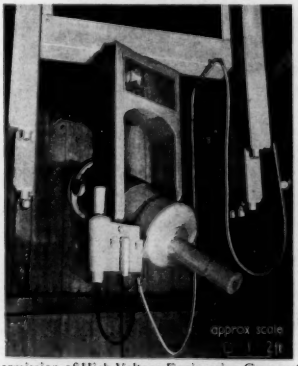

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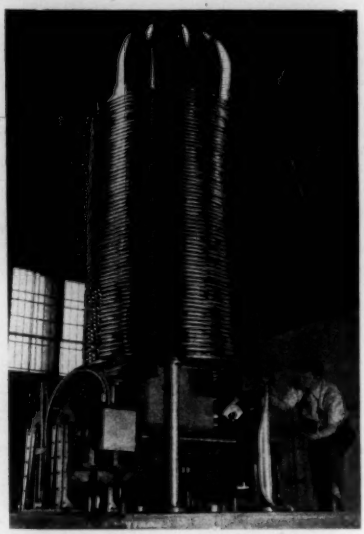
Fig. 8. 2 MeV electron accelerator

of the magnet, *F*, (Fig. 6). Electrodes H_1, H_2, are placed just above and just below the emerging beam, *G*, so that any change of voltage of the machine alters the currents intercepted by the electrodes. These currents can then be used to

control the voltage. Since the belt takes about 1/10 sec to move from the bottom to the top pulley, variation of the spray current is only of use in controlling slow variations. Rapid control can be obtained by modulating a beam of electrons which passes up the second acceleration tube, E_2, and forms an artificial load. The response of such a system is very rapid but it has the disadvantage that above 2 MeV the intensity of X-rays generated by the electron beam is becoming excessive. An alternative method is to supply a controlled load by a corona discharge through the gas insulating the machine. The load is varied by means of the voltage of the electrode, Q, surrounding the corona point, P, this voltage being determined by the currents to the electrodes H_1 and H_2. Though slower than the electron beam system it appears to be adequate for nuclear experiments. By such methods the voltage can be held within a kilovolt (100 V has been claimed) though it is not easy to measure the degree of control. Over periods of 1 hour or more we have found slow drifts, perhaps due to slow changes in the field of the analysing magnet and we are hoping to avoid these by referring our voltages to sharp nuclear resonances.



(By permission of High Voltage Engineering Corporation)

Fig. 9. Electron accelerator 3 MeV, 4 mA, 12 kW of ionizing energy, capable of sterilizing 5000 lb of material per hour

Accurate absolute measurements of voltage are not easy to make. Once calibrated, a generating voltmeter[4] provides fair accuracy, but precision work requires, for instance, deflexion by a known electric field produced between accurately-made deflecting plates.[5]

2. *Production of intense sources of mono-energetic neutrons.* For most nuclear physics work the emphasis is on voltage and voltage stability rather than on large currents. By producing a large current of deuterons (250 μA or more) at a moderate voltage (1 MV) and using it to bombard deuterium or tritium targets a powerful beam of mono-energetic neutrons can be obtained, comparable in flux density with those from nuclear reactors, which do not, of course, produce mono-energetic beams.

3. *X-rays.* A few hundred microamps of electrons at, say, 2 MeV can provide a very powerful source of X-rays—hundreds of roentgen per minute at a metre—equivalent to several times the radiation from all the mined radium in the world. The value for cancer therapy is obvious, particularly for deep therapy, where the patient is rotated so as to get an intense dose on a given small volume with relatively small intensity elsewhere.

For industrial use the machines are particularly useful; partly because the electrons producing them are of constant high voltage, not fluctuating as in resonating-transformer sets; largely because the focal spot is small so that the shadows cast are very sharp. A 2 MeV machine at 250 μA will give a clear picture through 5 in. of steel in 1 min, as effective as 2000 curies of radio-cobalt 60. The machines can be tilted and orientated without difficulty. (See Fig. 8.)

4. *Electrons.* A large fraction of the electrons, 100 μA or more, can be extracted through a thin window and used for the treatment of superficial lesions. The results recently obtained are surprisingly good.

5. *Sterilization of food and drugs.* This is usually carried out by heating, but the use of electrons and X-rays offers the advantages of a fast, continuous, accurately controlled process. A high intensity is required and the optimum voltage is about 3 MeV. Fig. 9 shows a large machine giving a 4 mA beam and capable of sterilizing 2 tons of material per hour. To get uniformity over the sample the beam is scanned backwards and forwards. Good results with certain delicate pharmaceutical products have been obtained, but up to now there have been unpleasant side reactions with food. It is obviously a promising field, and may open up a large demand for electrostatic machines.

ACKNOWLEDGEMENTS

I wish to express my thanks to the English Electric Co. Ltd., who were responsible for the construction of the greater part of the generator in the Cavendish Laboratory, to the High Voltage Engineering Corporation for much useful advice and for permission to reproduce Figs. 7(*a*), 7(*b*), 8 and 9, and to the Corning Glass Works for permission to reproduce Fig. 5.

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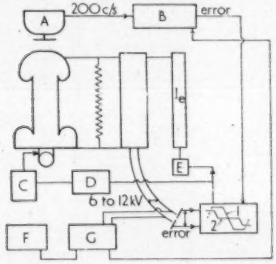
Note on the voltage stabilization of an electrostatic generator

By D. R. CHICK, M.Sc., F.Inst.P., and E. K. INALL, B.Sc., B.E., Research Laboratory, Associated Electrical Industries Limited, Aldermaston, Berkshire

A multiple-loop servo-system is used to control and measure the energy of an ion beam from a 500 kV electrostatic generator to 1 part in 10^3. A modulated electron beam is used to provide fast correction of the generator potential over a range of $\pm$ 150 kV. With 15 μA of control electrons, the X-ray intensity in the target room is increased from 0·07 r per 8 h to 0·10 r per 8 h.

To gain experience on the stabilization and use of a pressurized Van de Graaff generator, an air insulated generator and ion accelerator tube, having a maximum operating voltage of 500 kV, were built. The control system, shown schematically in the figure, has been developed and tested on the air insulated machine. Initially, the generating voltmeter control circuit described below was used to provide a stability of 1 part in 200 over periods of about 4 h.



Schematic diagram of generator stabilizing loops

A, generating voltmeter; *B*, amplifier; *C*, spray stabilizer controlled through *D* by average value of error signal; *E*, electron gun; I_e, control electron current; *F*, standard cells and potentiometer defining *G*, the deflector supplies; Curve 1, analyser error symbol; Curve 2, generating voltmeter error signal.

The generator is a constant current source connected to a resistive load of 10^{10} Ω. Its voltage, and hence the ion energy can therefore be controlled by varying an electron[1,2] current passing in the reverse direction, through the same tube as the ions. This current is controlled by an error signal obtained as the difference between the rectified output of the voltmeter and a stable reference voltage. The stabilizing system made up of the generating voltmeter, error signal amplifier and electron beam to the high-voltage electrode, has a loop gain of 5000 for slow variations, dropping to unity at about 25 c/s. The upper frequency limit of the response is set by the filter required to smooth the 400 c/s ripple inherent in the error signal derived from the voltmeter.

The mean value of the electron beam is maintained at 15 μA, while the instantaneous value can be modulated from 0 to 30 μA. With this change of electron current the generator voltage could be varied over a range of $\pm$150 kV by altering the reference voltage setting.

The average value of the error signal is derived from a circuit having a 2 sec time constant, and this average value is used to control the generator excitation through the exciter current stabilizing loop. This second loop is arranged so that an error signal requiring an increase of electron current produces a decreased charging current. With the double loop system, generator load variations are initially compensated by a change in electron current followed by an assisting change in the charge current. Hence, changes in excess of the electron beam control range will be corrected by a slow change in the charging current. Owing to the limited range over which the charging current can be stabilized it is necessary to set the charging current manually for the energy region selected.

When the accelerator tube is working at 500 kV, with secondary electron suppression as described by Inall,[3] the X-ray intensity in the target room, with no control electrons, is less than 0·07 r per 8 h. When a control electron beam of 15 μA is used, the X-ray intensity increases to 0·1 r per 8 h.

Over a period of 12 months, the voltmeter has often been calibrated by comparison with a resonant nuclear reaction (^{7}Li(p, γ)^{8}Be) and the greatest variations observed were +1 part in 200 and −1 part in 100. The voltmeter was shown to be linear, to the accuracy of the indicating instrument, by measuring the momenta of the components of a deuterium ion beam.

The final aims were to reduce the short-term variation in the ion beam energy to less than 1 part in 10^3, and to measure the energy with an absolute accuracy of 1 part in 10^3. This was done by taking an error signal from the exit slit jaws of an absolute electrostatic analyser.[4,5] The constancy of the target current obtained was taken as an indication of the efficiency of the stabilizing loops, and target currents of up to 25 μA have been obtained for long periods when the slits were set for an energy resolution of 1 part in 10^3. The short-term variations in target current were of the order of 1 μA and currents intercepted on the exit slit jaws were of the order of a few microamps.

The setting of the deflector voltage, applied to the electrodes of the electrostatic analyser, controlled the potential of the generator over a range of about $\pm$150 kV as predicted, and in practice manual adjustments were made to the charging current to keep the mean electron beam current to about 15 μA for each setting. The generating voltmeter servo loop is still required to correct any error greater than $\pm$1 part in 100, since with errors larger than this the ion beam strikes the electrodes of the analyser.

ACKNOWLEDGEMENTS

The authors wish to thank their colleagues for many helpful discussions and in particular B. Millar and J. Churchill for help in developing the stabilizing system, and S. E. Hunt, who was responsible for the electrostatic analyser. They also desire to thank Dr. T. E. Allibone for permission to publish this paper.

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Ten years of research on electrostatics at the University of Grenoble 1942–1952

By Professor N. J. Felici, University of Grenoble
(Translated by A. M. Cassie, M.A., F.Inst.P.)

The emphasis is on the practical development and application of electrostatic generators, rather than on theoretical considerations.

The small cylindrical compressed-gas generators with conducting segments proved very satisfactory for powers of the order of 30 W at voltages of 70 kV. In attempts to increase the output multiplate generators with conducting segments were evolved which reached 750 W at 250 kV, but beyond this range difficulties of mechanical construction proved formidable. After disproving the current view that charge slip was responsible for the low output of moving insulator machines, a cylindrical generator of this type was constructed with highly encouraging results.

Further development continues.

Research on electrostatics was started at the University of Grenoble on the initiative of the author at the end of 1942. The work was carried on with very little assistance, and despite very great difficulties, until the end of the occupation in 1945. At that date researches had proved so promising that it was decided to set up a special laboratory at Grenoble for development.

At the end of 1946 a private company was formed in Grenoble for the practical exploitation of patents and inventions arising from the work at the University. (Société Anonyme de Machines Electrostatiques or SAMES). This Company has developed rapidly and keeps in close and constant contact with C.N.R.S. (Centre National de la Recherche Scientifique) at the University. In 1951 a branch company was formed in America, SAMES Inc., with the object of co-ordinating the work of the French company and the numerous interests in electrostatic devices.

State of the art regarding electrostatic machines in 1942

In 1942 the only work of importance on electrostatic machines was that of Van de Graaff and of Trump, who for six years had been developing the belt type of generator. It was not the author's intention to enter the field in competition with the belt generator but rather to develop the principles on which electrostatic machines functioned in a manner which would make them useful in numerous industrial applications where up to that time they had been completely neglected. Actually, there are numerous applications which require voltages between 10 000 and 200 000 V which are easy to realize with the old electrostatic machines; such equipment had never been used because of its low power and erratic operation.

It was natural, therefore, to consider whether it would be possible to perfect the belt type of machine or whether one should attempt some entirely different construction. In 1942 the belt type machine had near enough reached its maximum performance. This performance was remarkable in the magnitude of the voltage it could produce but, despite the use of compressed gas known since 1886, the power produced remained relatively small considering the size and cost of the machine. This, of course, was of little importance for the applications envisaged by Van de Graaff, whose main object was to produce very high voltages for nuclear research, voltages which it was very difficult to obtain by other means. For applications at lower voltages such as 100–200 kV a small belt machine had proved incapable of competing with other systems. According to the literature on the subject the belt generators had attained their limit because it appeared impossible to increase to any extent the mechanical forces to which the belt was subject or to increase its speed. Indeed, in all electrostatic generators the electric power developed necessarily depends on the work done against the electrostatic forces applied to the moving member carrying the electric charge. The power is determined by the work done against these forces per second, i.e. by the velocity of the moving part. However, there was no question of increasing the belt velocity in the Van de Graaff machines, since the friction of the belt in the compressed gaseous medium would have reached very considerable proportions. The frictional losses increase as the cube of the velocity so that even a slight increase would hardly be practicable.

It did not appear that there would be any possible way of increasing the electrostatic forces on the belt. According to current knowledge the density of the electric charge carried by the belt remained very limited, even in a compressed gas medium, and the electric field acting on this charge density had already been pushed to considerable values, approaching the limit imposed by breakdown. In the best designs of apparatus the useful forces acting on each square centimetre of the belt reached about 600 dynes. The speed was of the order of 25 m/sec and the power was only about 0·15 W/cm^2 of the belt surface.

However, it seemed that much larger powers should be possible. The charge density on the surface of an electrified body is limited only by the ionization of the surrounding gas. The critical field strength producing this ionization is approximately proportional to the pressure, so that the surface charge density should increase in the same way. Accordingly, a machine working at a pressure of 20 atm in air ought to give a current about fifteen times as great as at atmospheric pressure. Again, the voltage which can be applied between the conductors, being proportional to the field strength between them, ought also to be more or less proportional to the pressure. Hence, the power of an electrostatic machine ought to increase approximately as the square of the pressure or, more accurately, should be proportional to the square of the maximum field strength to which the gas can be subjected. This field strength or dielectric strength of the gas is known up to pressures of several tens of atmospheres, so that it should be possible to predict the power of an electrostatic machine at say 20 atm and it should then be around two hundred times greater than that at atmospheric pressure. The belt type machine did not in any way follow this law. The power at the highest pressures did not reach more than five or ten times that at atmospheric pressure, even under the most favourable conditions.

The reasons for this enormous difference were not very clear. Many authorities attributed it to defective adherence

of the electrostatic charges to the belt, a difficulty which prevented the belt from carrying, under voltage, the charge density permitted by the dielectric strength of the medium. It was presumed that the charge suffered displacement or slip along the belt as a result of the electric field produced by the poles of the machine. It had been noted in effect that the current produced by a belt machine under short-circuit conditions could be quite considerable, but generally fell off very rapidly as the potential delivery by the machine was increased. It appeared, therefore, that the tangential field created along the belt caused a flow of the charge along the belt by reason of its poor adherence, and this flow was responsible for the considerable drop in current with increase of voltage.

INITIAL EXPERIMENTS WITH CONDUCTING ELEMENTS

In view of the results just discussed it appeared that there would be little point in attempting to perfect the belt type of apparatus in order to increase its power, and so an arrangement was sought which would permit the use of considerable electrostatic forces without the risk of the charges being displaced. The author accordingly considered the use of conductors. The electrostatic forces exerted on a conductor are always perpendicular to its surface and so movement of the charges is impossible. Only ionization of the ambient gas can cause the disappearance of charges and forces, and therefore one ought to be sure of obtaining considerable forces under reasonable pressures. In air at atmospheric pressure the critical field strength is around 30 kV/cm and the maximum force 0·4 g/cm^2, which is very small; but at a pressure of 30 atm in air the critical field is at least 600 kV/cm, i.e. twenty times larger. The force per square centimetre is accordingly four hundred times as great, and therefore could reach 160 g/cm^2 which would be of some interest. From these considerations it should follow that an electrostatic machine, where the moving members are conductors, ought to have a power increasing as the square of the dielectric strength of the gaseous medium, and which might, for example, be four hundred times at a pressure of 30 atm compared with that at a pressure of 1 atm in air.

At the beginning of the author's researches an attempt was made to verify these theoretical conclusions with a very simple piece of apparatus which was a replica of a very old machine constructed by the German Professor Toepler in 1865 (Fig. 1). This apparatus consisted simply of an insulating disk on which were fixed two semi-circular conducting segments separated from each other and which passed in front of a fixed inductor. By the action of two brushes each conducting sector was connected to earth when its capacity with respect to the conductor was a maximum, and brought into contact with an insulated terminal when its capacity was a minimum. Thus, it became charged with a certain quantity of electricity under zero potential, this being given up to the receptor at a greater potential. The apparatus therefore constituted an actual generator. However, it was evident that one would not expect very good results by putting such an apparatus under compressed air because the intense electrostatic forces which had been expected were actually exerted across a section of the elements, and this section, in the original Toepler apparatus, was too small to allow reasonable forces. In these old machines the elements had taken the form of simple sheets of tin foil of negligible thickness.

A mathematical study was then undertaken to determine the optimum proportions of the moving elements, taking into account the distance between each element and the fixed inductor, so as to assure throughout a uniform dielectric stress on the ambient medium. This study showed that it was necessary to give the element a thickness equal to the distance of its separation from the inductor in the case when the conductor is charged on only one side (Fig. 2*a*), and equal to double this distance when the conductor is under stress on

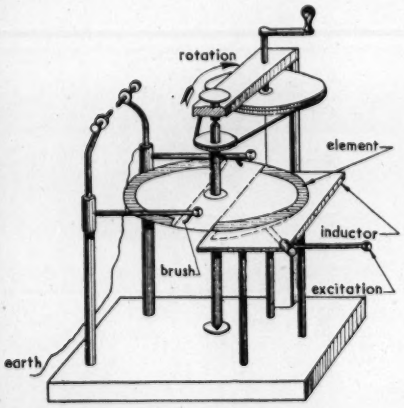


Fig. 1. Toepler's original machine

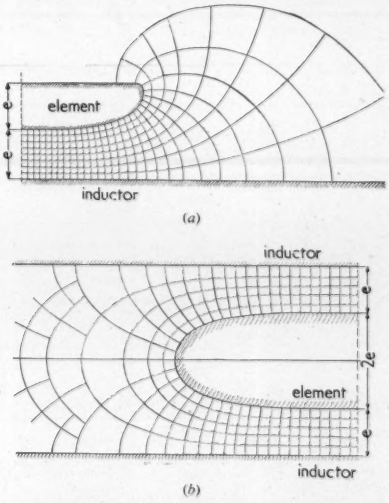


Fig. 2. Theoretical profile for constant dielectric stress
(*a*) Conductor charged on one side.
(*b*) Conductor charged on both sides.

both sides (Fig. 2*b*). When the thickness of the element is chosen in this way, and when the section is given the ideal profile, which one can calculate theoretically, one can be sure of making use, without risk of ionization, of all the potential energy of the condenser formed by the element and by the inductor. As the potential energy of the condenser increases as the square of the dielectric strength of the gaseous medium the power of the machine ought to increase likewise for a given speed.

Fig. 3 shows the apparatus constructed by Morel in 1943 according to the above principles and which completely

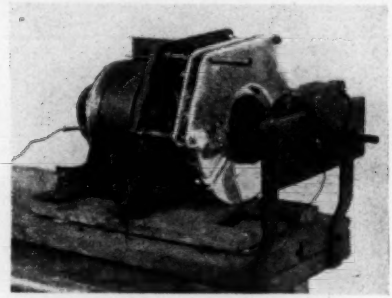


Fig. 3. Morel's apparatus

verified these theoretical conclusions. The power was in fact multiplied by a factor of two hundred and fifty when the pressure changed from 1 to 30 atm, a factor which represents exactly the square of the ratio of the dielectric strength of air between plane aluminium electrodes at 1 and 30 atm. Thus it had been demonstrated that the power of electrostatic generators can, by means of correct construction, be effectively proportional to the square of the dielectric strength of the gas, and the production of considerable powers at practicable pressures became possible.

The first apparatus constructed by Morel had on account of its small dimensions quite a small power, 6 W at a speed of 1500 r.p.m. and at a pressure of 20 atm. In order to investigate the above principles further, the construction of a much bigger machine was undertaken (eight elements per disk instead of two, and five disks in place of one). Despite the great difficulties in obtaining materials this apparatus was finished at the beginning of 1944, and the experiments were conclusive, taking into account the imperfections of its construction. This generator developed 250 W at a speed of 1500 r.p.m., i.e. an output of 5 mA at a voltage of 50 kV. Its efficiency was very high, of the order of 80%, the only losses being due to the unavoidable friction of the moving elements in air compressed at 25 atm.

FIRST INDUSTRIAL APPLICATIONS: CYLINDRICAL GENERATORS WITH CONDUCTING SEGMENTS

At the end of the war contacts between industry and the laboratory became closer. It became evident that a small, very light generator giving powers of several watts and proving reliable in operation would be capable of several applications. It was thought that it could be used as a portable generator for precipitation of powders and mists in the treatment of crops; for supplying high voltage to infra-red image converters. These applications appeared to be very suitable for the new machines, and the construction of very small generators based on the same principles as the disk machines discussed above was undertaken in 1946. On account of the smallness of the power required, the stator and rotor were made of segments having a cylindrical shape instead of plane elements and multiple disks (Fig. 4). Several

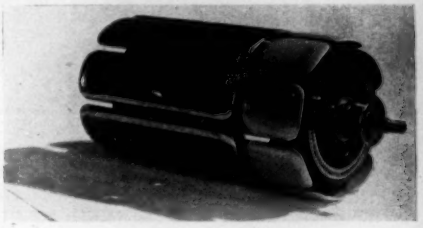


Fig. 4. Rotors of a cylindrical generator

On left: principal rotor; *on right:* exciter rotor; diameter: 14 cm; length of principal rotor: 18 cm; clearance between stator and rotor: 0·25 cm; voltage: 70 kV; current: 0·4 mA at 1500 r.p.m., 0·8 mA at 3000 r.p.m.; gas used: air at 25 atm.

prototypes were tried out in the laboratory giving voltages between 20 and 60 kV with an output of the order of 0·1 mA. The main problem with such generators was that of providing a mechanical drive, by hand for example, through a gas-tight packing which would be very simple and yet avoid loss of gas. Here the first practical success of these new electrostatic generators was achieved. Extremely successful trials were carried out on the spraying of crops with dust. At the same time it was possible to replace by a small generator weighing about 2 kg the enormous system of rectifiers which had been employed by the Germans for supplying infra-red image converters.

At this time SAMES started to produce a small series of these generators. There were two main types: one producing 0·1 mA, the other 0·4 to 0·8 mA according to speed (the high speed could not be maintained permanently because of the rapid heating of the compressed gas). For both the voltage was 60 to 70 kV. Two other notable achievements of SAMES deserve mention: the arrangement of electrostatic generators in series, and the development of an electrostatic ignition device. The series coupling of generators permits the production of voltages which up to the present time have reached 250 kV.

In a very different field, considerable effort had been devoted to the provision of a special generator for ignition in internal combustion engines. This generator (Fig. 5) provided a very satisfactory solution of the problem of ignition and is considered to be superior to the methods already known. This machine has the important advantages of being completely independent of batteries; of providing sparks of the same intensity at all speeds; and most important of all, of providing ignition totally independent of the insulation resistance of the sparking plugs, of oil films, etc. The minimum sparking plug resistance at which a coil will operate is of the order of 500 000 Ω. With this new device it can be as low as 250 Ω. This electrostatic ignition system is most interesting and has created abroad, particularly in America, sufficient interest to make industrial development on a large scale probable.

At the same time SAMES continued to manufacture and improve considerably the very light generators for providing power for infra-red converters which, however, cannot be described in detail for reasons of secrecy. All these machines, as will be seen from the figures, are of the cylindrical type; rotor and stator are formed of segments of cylinders and are separated from one another by a distance of the order of

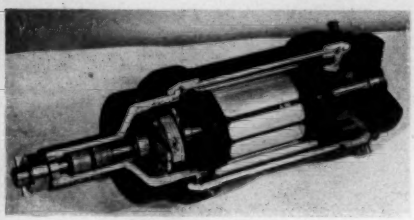


Fig. 5. Electrostatic generator for ignition in internal combustion engines

1 to 3 mm. Much could be said on the practical problems raised in the development of such machines, many of them entirely novel, and particularly on the very successful use made of new plastic materials such as Araldite.

While indicating briefly the successes of these new generators, one ought at the same time to point out the limitations and defects. The field of application for these generators lies in the realm of voltages between 20 and 200 kV, particularly where reliable operation is needed. They can be driven equally well by petrol engine, by crank or by electric motor. They do not constitute any danger, and they can be multiplied for higher voltages without any risk. These are considerable advantages which justify the good reception they have had in several applications.

Unfortunately, however, the electrification of chemicals for the treatment of crops has not succeeded for economic reasons. Electrification should have made it possible to save three-quarters of the chemicals normally used for treatment. Unfortunately, farmers were not disposed to buy relatively expensive apparatus in order to effect such an economy, the chemicals being maintained at a low price by the Government. Thus the commercial exploitation of the electrification process for the treatment of plants has been hindered.

From the figures quoted it is evident that the current in the above machines is relatively small, in all cases less than 1 mA, and this is a limitation. It results from the use of the cylindrical type of machine which does not, as in the case of multiple disks, provide much surface area. Another defect appeared during service: the brush gear, while advantageous for excitation of normal machines, suffers accelerated wear as a result of the inevitable sparking, wear which limits the life of a generator to a maximum of a thousand hours. In an ordinary machine it is only necessary to replace these contacts and remove the dust produced, but this replacement is not so easily made in electrostatic generators since the gas-tight cylinder must be opened.

In view of the relatively small power limit of the cylindrical generator, work on the disk type of machine was started again in 1946, initially on the multiple disk apparatus used by Morel. Funds were provided for a model of considerable size (Fig. 6), consisting of 6 disks each of 12 sectors which would furnish 2 to 3 mA at 250 kV. This apparatus was in operation at the end of 1947, firstly as a single unit and then as two units of opposite polarity giving double the voltage. This machine has been very useful in the laboratory as a source of high tension for numerous experiments. In addition, it has been lent for a year to the Electricité de France to carry

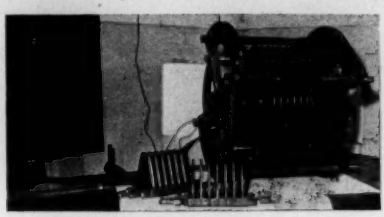


Fig. 6. Complete multiple disk apparatus. The stator is removed in sections

External diameter of rotor: 39 cm; clearance: 0·4 cm; voltage: 250 kV; current: 2 mA at 750 r.p.m.; gas used: air at 30 atm.

out investigations on the effects of corona on d.c. overhead lines.

Though the results obtained with the disk type of machine were satisfactory, great difficulties were encountered in constructing the rotating parts. These parts are made of metal, have considerable weight, and are supported by flanges of plastic insulating material keyed to the shaft. Hence the geometrical positioning of the elements on the rotor depended on pieces whose mechanical rigidity was relatively weak. Centrifugal forces and other causes slightly displaced the groups of sectors because of the deformability of the insulating flanges. As a result, despite the fact that it was possible to adjust the individual position of each group of elements initially, this position was not maintained, and hence it was not possible to work to the clearance between the stator and rotor originally intended. The separation at places became greater, at others less, and these became regions which limited the value of the power by setting up discharges between the segments of the stator and those of the rotor. It was necessary to readjust the elements fairly frequently (once a month), a matter acceptable in a laboratory but impossible in an industrial machine. Experience having shown the importance of this mechanism and of geometrical factors in general, a study was undertaken of a multiple disk machine in which all insulating parts were eliminated from the rotors. The resultant rotor, called a "Monobloc" (Fig. 7) consisted

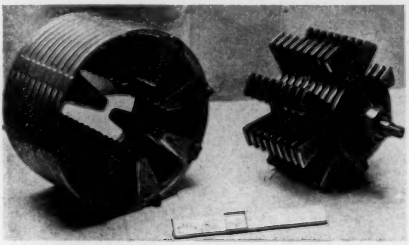


Fig. 7. "Monobloc" apparatus in which no insulating parts are used

On left: stator; *on right:* rotor.

of a stack of entirely metal disks, each disk comprising eight elements. A certain number of disks (five to ten) were screwed tightly to the axle. It was hoped in this way to obtain a much more accurate positioning of the elements and to avoid variations of separation in use. The model was built in 1950 and was designed for 70 kV at 10 mA. During its construction it was found that the alignment for parallelism and equidistance of the elements did not attain the standard of precision necessary, because although individual errors were themselves small (1/100 mm) these became additive in the construction of the complete stack. In the end the structure was no better than that of the previous model, and since no form of adjustment was possible it had to be admitted that the construction of an accurate multiple disk machine presents extremely difficult problems. Another disadvantage also appeared: sparks between metal surfaces are a random phenomenon depending on the presence of accidental impurities in or on the surface and so the risk of sparking between surfaces becomes greater as their area increases. Hence for a disk machine where the surface area is considerable the electric field, which can be maintained with certainty between the stator and the rotor, is measurably less than for small cylindrical machines.

MACHINES WITH INSULATING ELEMENTS (1951)

It thus appeared that machines with conducting sectors and multiple disks would prove difficult to realize on an industrial scale, and that it would not be possible to obtain powers greater than a few hundred watts, which was about the limit of the cylindrical machines with conducting sectors under construction.

At this time the attention of the author had been directed to the divergence of results obtained from different types of machines in which the moving elements carrying the charge were of non-conducting material. It appeared that the power limit was higher when insulating disks were used instead of belts as in the Van de Graaff machine. Several publications on machines with insulating disks claimed performances undoubtedly superior (in relation to surface area) to those of belt machines. From these contradictory results it could be concluded that the theory of slip or longitudinal displacement of the charges on the insulating belts was perhaps inaccurate and that the limitations of such machines resulted from some still unknown factor.

For this reason, at the beginning of 1950, the construction of a very simple experimental machine with an insulating disk was started at C.N.R.S. Its purpose was to investigate the question of charge slip. Experiments showed that there was no reason to suspect the adherence of electric charges to the insulator. The apparent slip could be explained by local ionization of the compressed gas. This ionization was due to the presence of parasitic electric fields proportional to the output voltage.

These conclusions, contradictory to generally accepted opinions, gave rise to the hope that it would be possible to use insulating transport disks under much greater forces, and hence obtain considerable increase in power. It is not possible to review the numerous experiments and difficulties by which the ensuing designs were eventually reached, but at this stage a number of principles can be enunciated which permit a very simple electrostatic machine to be constructed with insulating moving members and having an efficiency greatly superior to that of other systems. The moving insulating parts must have a geometry which will avoid any kind of vibration whatever during movement. The cylinder is the only shape which will satisfy this condition. The stator must be another smooth cylinder separated from the moving cylinder by a uniformly small distance, 0·2 or 0·3 mm. The static cylinder should be made of some material of constant resistivity of the order of 10^{11} Ω cm. Finally the ambient gas, instead of being electronegative (air, freon, etc.), should be pure hydrogen at a pressure of 10 to 20 atm. It is not possible to state briefly all the reasons which justify this choice since some are not yet completely known. In particular, the fact that pure hydrogen allows the current to pass very easily from a comb and acts as a very good insulator in other respects seems inexplicable. These two properties, apparently completely incompatible, are not exhibited by any other gas. Fig. 8

Fig. 8. Experimental insulating cylinder generator capable of producing 70 W

On left: Bakelite stator; *in centre:* Araldite rotor with axis; *on right:* supports for combs; clearance: 0·025 cm; diameter of rotor: 7·8 cm; voltage: 200 kV; current: 0·35 mA at 3000 r.p.m.; gas used: hydrogen at 20 atm.

shows the actual machine which produced a power of 70 W at 200 kV at a speed of 3000 r.p.m. The rotor and stator are simple plastic cylinders, the one an insulator and the other slightly conducting. The diameter is about 8 cm. It will be noted that unlike the belt machine and those described earlier, the loss due to friction in the compressed gas is negligible because of the low density of the hydrogen and the peripheral velocity is limited only by the centrifugal force. It can therefore be very much greater than formerly, all the more so because there is no mechanical friction between the rotor and the combs. All these advantages allow powers greater than 1 W/cm^2 of the effective area of the cylinder to be obtained at voltages of the order of 200 kV. Since the middle of 1951 results obtained in the laboratory have been so encouraging that improvements to multiple disk machines have been abandoned and all the available resources have been turned towards the perfection of the insulating cylinder type of machine. These machines present considerable advantages of simplicity, of increased power and voltage, and the connexion of a small number in series ought to produce voltages as large as those obtained with the belt machines, in addition to very much greater power.

Naturally, difficult practical problems have arisen for which complete solutions have not yet been realized: the moving cylinder is affected by the bombardment of the ions, and it is difficult to find a material whose resistivity is both high and well defined. For possible further developments it can be noted that the insulating cylinder type of machine can be made to function with two fluid dielectrics instead of only one. Pure hydrogen could be used on one side of the cylinder in the space where ionization takes place, and another fluid of better dielectric properties such as nitrogen, or even a liquid, could be used in the space between the stator and rotor. The power would then be found to be increased by the ratio of the maximum of the electric fields which will

exist in the fluid to the maximum field in the hydrogen. Experiments have already succeeded in which oil has been introduced into the interspace. It seems that this is a development which might lead to the production of powers of relative importance.

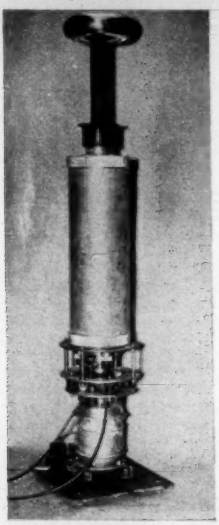


Fig. 9. Insulating cylinder generator capable of developing 230 kV

At the bottom: motor; diameter of gas-tank: 22 cm; voltage: 230 kV; current: 1·5 mA at 3000 r.p.m.; gas used: hydrogen at 15 atm.

CONCLUSION

It can be seen that during the last ten years the research at the C.N.R.S., and the work at SAMES, have systematically explored the practical possibilities of electrostatic generators from all angles. At the beginning efforts were centred solely on the machines with conducting segments, insulating segments having appeared impracticable for reasons which were eventually shown to be groundless but which, at that time, were universally accepted. These investigations have not made it possible to exceed powers of more than a few hundred watts in industrial equipment because of unexpected difficulties of mechanical construction. On the other hand, in the domain of small machines it has been possible to make apparatus on a practical scale which will function reliably and maintain a definite polarity. An ignition system for internal combustion engines represents perhaps the greatest achievement. After having studied the use of conducting segments for eight years and having finally decided against their use for high powers, a scientific study of insulating charge transporters has revealed that the limitations of belt machines or those with insulating disks previously assumed were completely false. This conclusion is perhaps the most noteworthy advance made at this electrostatic laboratory. The aim of the work has not been confined to demonstrating the limitations of accepted ideas, but has endeavoured to pose new principles on which the insulating cylinder type of machine can be developed. At present these machines (Fig. 9) will give voltages above 200 kV with an output of 1 to 2 mA, i.e. they already provide powers of the same orders as the most advanced machines with conducting disks, and therefore it may be hoped that the limits of this new system of generators are still a long way off.

DISCUSSION

Mr. J. H. McGuire: I also am interested in the electrostatic generator for ignition in internal combustion engines, and I should like to ask about the engineering aspect of its application to variable speed engines and its operation on starting. Is the generator driven at a constant speed, with a limitation on the rate of delivery of sparks, thus giving a constant equilibrium voltage? Alternatively, is the generator voltage not allowed to reach equilibrium but driven by the engine so that generator speed compensates for increased spark delivery requirement, again giving an approximately constant voltage? This latter operation, if possible, is near to the ideal of efficiency.

Dr. E. C. Craven: What does Professor Felici imply by the term "pure hydrogen"? In hydrogenation work one is pleased if significant impurities (carbon monoxide in particular) can be reduced to a few parts per million. What are the significant impurities in the electrostatic application and how are their amounts determined?

Mr. E. S. Shire: Firstly, purity is a relative term and electronegative impurity of one part in a million rapidly traps electrons at atmospheric pressure and more so at high pressures, as is shown by the difficulty of extracting electron pulses from high-pressure hydrogen ionization chambers used in nuclear physics. In Professor Felici's generators, hydrogen might behave as pure hydrogen near the corona points, where the electron density could be high, and as impure hydrogen elsewhere.

I should like to ask: how stable is the voltage given by the generators?

Dr. R. Fürth: Is it really justifiable to call these machines, which generate considerable electric currents, "electrostatic"? I think the word should be restricted to describe phenomena of *static* electricity. I suggest that these machines should rather be called "electric induction generators" as distinct from "electromagnetic generators."

Author's reply: In our earliest experiments on ignition, the generator was driven at a constant speed by a small d.c. motor fed by the battery. We found this arrangement inconvenient in practice, for it requires constant generator voltage, which is not a natural feature of any electrostatic machine. So we turned to a generator driven by the explosion engine itself, thus giving constant spark delivery independently of the speed. The sparking voltage remains fairly constant from 1 r.p.m. to 3000 r.p.m.

Our "pure" hydrogen may contain one part in 10^4 of electronegative impurities. It is purified in the hydrogen liquefier of the University. We felt no need for any further increase in purity. That may be explained, as pointed out by Mr. E. S. Shire, by the very high electron density near the ionizing blades, which is sufficient to saturate the impurities, making them harmless in practice.

The voltage stability has not yet been studied. The natural voltage fluctuations may be of the order of 1%. No ripple, however small, can be detected.

Survey of harmful static electrification

By H. W. SWANN, O.B.E., M.I.E.E., Senior Electrical Inspector, Factory Department, Ministry of Labour and National Service

A survey of the history of harmful static electrification in industry is given together with examples and various remedies considered.

It is not easy in statistical terms to evaluate what is happening as a result of harmful static electrification. In fact, the only real statistics I have which are worth while, are that fires and explosions attributed by the fire brigades to static electrification result in from twenty to thirty calls per annum. Thirty calls must be very much less than the number of troubles which are experienced as a result of static electrification in industry and elsewhere, but it is curious to find that an average of about twenty-five has been returned by the fire brigades to the central statistical department for quite a number of years.

I had no experience of any problem connected with static electrification when I joined the Factory Department. One of the first things which I had to investigate was an explosion in a margarine works where there was a good deal of dry powder and husk from ground-nuts discard being cycloned across to a silo. Two men were trying to find out how much of this dusty stuff there was in the silo; they lowered a portable electric hand-lamp with a lead into the silo to find out, and the whole thing blew up. The two men, unfortunately, lost their lives, so that we could not obtain from them an idea of what led up to the explosion.

I was faced with the suggestion that it had been initiated by a static electric spark in the dust, which was very thick and heavy, and later I saw the operation repeated in another silo. On the other hand, it might have been caused by the coincident failure of the unprotected electric hand-lamp. It was very difficult to decide, especially as this was my first intimation that dust could explode, given the right conditions. I attributed that explosion officially to a failure of the electric hand-lamp, but I am far from sure, looking back over the years, that it was not due to static electricity which, from what I have been told since, can result from exactly the conditions which were described to me and which I saw myself when I investigated that explosion.

I remember, too, being called in to deal with difficulties arising with cellulose sheet packing. Those were the days when cellulose acetate processes for the making of packaging for materials were just beginning, and the manufacturers could not make the cut sheets of cellophane lie down flat one on top of the other. I was asked to advise on the subject, and did not know what to do. I suggested that this static electrification might be dispersed by using X-rays, but when they found out the price of an X-ray machine and the cost of running it they did not like that idea. How they managed in the end to squash one sheet of cellophane down on the other I do not know.

That brings us to the general subject of textiles, and the difficulty with fog marking in the manufacture of fabrics. If a machine stops, and if the conditions are such that the dust in the atmosphere is attracted to the electrified textile threads, this dust is clearly discernible when the machine starts up again. This "fog mark" is very detrimental to the quality of the material. Quality is perhaps not quite so much my concern as safety, and on the safety side the "harmful effects" were more in connexion with the early types of high-voltage neutralization equipment than with the electrostatic charges. I remember being called to one of the very large textile concerns and being given the details of a high-voltage neutralizing circuit consisting of a 10000 V, 50 c/s transformer, with a label on which the characteristics were clearly stamped, from which I learned that the current was rated up to 1 A. The h.t. lead from this transformer was taken straight to the neutralizing device, a long cylinder with spikes sticking out of it, immediately under the hand and wrist of the operator. The harmful effects of static were completely excluded from my mind when I saw this arrangement for neutralizing. I was told that I was being shown it in strict confidence, because it was a new departure and it was thought that competitors had not got so far as this wonderful piece of apparatus, which certainly did stop the fog marking. My attention was devoted entirely to the treatment of the neutralizer, and it is reassuring to know that the latest types, which I have had the advantage of seeing in the last 12 months, seem to be very well designed and to be entirely safe from the point of view of shock effect on the person and effective in neutralizing.

There seems to be more difficulty in applying the principle of the use of radioactive materials. A good deal was heard about this a year or two ago, but I understand that there are certain difficulties in preventing risk of injury where there is no specialized supervision. We may be able to get some help on this from Harwell and Amersham, and I learn with interest of the advisory service now offered. I think that it is a line of attack which may very well be successful, but the conditions must be controlled.

Going back again to those early days, and thinking of the general problem as it came to me by bits, I remember the difficulty of getting reliable guidance. There were no focal points to which I could turn for information, while the guidance which it was possible to obtain from scientific organizations was not easy to turn into practical applications. We had to make use of our own resources.

Explosions in the dry cleaning industry assumed somewhat disquieting proportions in the middle 1920s, and we were faced with a problem with which it was inherently difficult to deal and which undoubtedly demanded fundamental research, which to the best of my belief it never had. The trouble was not quite the same in each case, but it was usually associated in some way with the tumbler washing machines, which might hold 500 gallons of benzol, the drum or barrel oscillating slowly, after which the fabrics were rotated at 300–400 r.p.m. in a perforated cage to throw off the benzol, which was extracted by pumps. When the manhole was undone in order to unload the machine, the interior would be nearly empty of benzol but actually just at the most explosive point having regard to the intake of air which took place immediately the manhole was lifted. In my experience, it was at this moment that an explosion was most likely to take place. Explosions took place when the manhole was lifted without, apparently, any other action or movement by the person concerned. Explosions also occurred when workpeople put their hands

inside to pull out the first garment, and also during rotation. We reached the conclusion that in all probability the number of explosions during rotation would be considerably increased were it not for the fact that the mixture of benzol and air inside was normally far too rich to be ignited and, that if, as I suggested at the time, someone would make a little glass model of the machine and work it in the dark, static sparks would be visible during the whole of the time that the machine was in operation.

It thus became, to my mind, critical to regulate the supply of air into the machine when the manhole was opened, and we got so far as to suggest that carbon dioxide or inert nitrogen should be blown into the washing machine either before, or as soon as possible after the manhole cover had been removed. Whether that was ever done I do not know, but several firms did in fact put in fairly comprehensive carbon dioxide installations which enabled them to drown any fire which broke out, and we were careful to have handles and control levers fixed by the door on the outside so that people could open the door first and switch on the carbon dioxide afterwards, and not in the reverse order, which is sometimes arranged.

We referred the dry cleaning problem to the National Physical Laboratory, who gave us a good deal of assistance. They visited cleaning establishments and carried out a number of bench experiments on the electrification of different fabrics, and finally suggested that the danger could be reduced by making the washing liquid, benzol or white spirit, conductive by the addition of magnesium oleate. I thought it was an answer, but it was not, because the first two or three washes ran away with all the magnesium oleate. The customer whose clothes were in the wash on the first day that the magnesium oleate was put in got a good dose of it, which he probably did not like, but the next lot got far less, and so on, and test measurement of the benzol or white spirit showed that the specific resistance rose rapidly after two or three washes.

The risk has been minimized considerably in recent years by using a spirit with a higher flashpoint, but I do not think that we really know much more about the underlying electrical causation to-day. I express this opinion with a good deal of reserve, because other people may very well know far more than I do, but I have heard very little more about dry cleaning troubles recently, and it remains in my mind on much the same basis as 20 years ago.

In industrial work, one of the interesting things which I was sometimes taken to see when I first inspected factories was some sort of belt on a pulley where there were often sparks across the vee. I do not think there was very much risk arising from plain, straightforward belt sparking under conditions where no inflammable vapour dust or material was used. The same phenomenon arises in paper making, where one can both hear and see the long sparks which occur in any warm paper-making room at the end of the machine, where the dry, hot paper is put on the final reel. It is a different story, however, under certain exceptional conditions, and I have heard of an extraordinary case which occurred in a cotton mill, where a multiple cotton rope formed the main drive from a steam engine. This was running in a rope pit alongside a steam vessel, itself under pressure and at a temperature of approximately 700° F. A disastrous fire occurred, and after investigation it was thought that there had been a pressure leak in the steam pipe which set up a static charge, resulting in sparking to the cotton waste lying in the pit. It was an assumption, and must remain an assumption, that this smouldering material was fanned into a fierce blaze by the draught from the pulley. This set fire to the wooden floor above the pit. That is what we assumed happened and we have not had a better explanation, though a number of explanations were suggested which we thought were worse.

I turn next to the far more serious sparking which occurs in rubber spreading. There are a number of cases on record where fires have occurred in rubber spreading work, where the solvent is naphtha. The trouble arose so frequently that it was often necessary in the works to keep one or more persons employed on the job of looking out for fires and swabbing them directly they occurred. (The same method at that time was adopted in the manufacture of matches of the non-safety type.) A serious fire very seldom occurred because it was never allowed to spread. The trouble that led to serious results was usually the ignition of the solvent in the hood which was installed in order that the solvent should be recovered. There, I think, you have the kind of condition where it may be that ionization, either by radioactive material or in some other way, could be useful. On the other hand, it may be that the processes, which now seem to be far less prone to this kind of risk, do not need overmuch attention, but if the trouble did break out again I think that it would be more controllable by scientific and exact means than was the case 20 years ago.

I remember an unusual case where a workman received severe burns from the addition of white spirit to rubber. The process was that of reducing raw rubber solution in white spirit. Steel rolls are used, rotating at different speeds, and after this operation the product is carried to a nearby mixer which also contains white spirit. The repetition of this process, which results in spillage, had coated the floor with a rubber deposit, and on the day of the accident an explosion occurred as a workman placed a slab of rubber in the mechanism. This was thought to be a case of personal charge equalization, to which I shall refer later.

Before the war I had been called in to a good many cases of electrification of the nozzle ends in shot blasting. In those early days we did not possess the advantages of conductive rubber of which to make the hoses, and we had to have complicated systems of embedded earth wires. The difficulty was really to persuade the workman to use a nozzle from which he got shocks because he, not unnaturally, thought it much more dangerous than it was.

We had rather a jolt during the war years when little factories which were engaged in the grinding of magnesium and aluminium for incendiary bombs and pyrotechnic powders experienced explosions. I found for the first time something which I did not believe at the time, but which proved to be entirely correct, namely that both magnesium and aluminium powder particles became almost non-conductors very soon after the grinding process. Experiments at the University of Birmingham showed that a pressure of up to 6000 V a.c. could be applied to opposite sides of a centimetre cube of finely divided magnesium powder on the bench before it would break down, so that we were dealing with a very difficult question, as was proved by the fact that explosions occurred, some attended by loss of life and destruction of property.

These explosions occurred sometimes in the ball mills, but more often in the pneumatic trunking which with a cyclone was used to shift finely-divided powders from one place to another, and also in sieving and grading. We found that we could alleviate the trouble to some extent by careful bonding of the metal components of trunking, and a technique of equipotential bonding was built up, but with considerable difficulty, because in order to make mechanical joints—that

is, to bond the ends of earth wires under a screw or washer or nut—the surface had to be absolutely free of magnesium or aluminium dust. The workmen did not understand that, and it was very difficult to achieve it in a room where there was always a slime or covering of aluminium or magnesium over everything. One could not touch anything in one of those factories without getting a smear on one's finger. However clean things were thought to be, a film remained and that film in itself was a serious difficulty in trying to obtain low resistance earthing. I have since been told, what I did not know at the time, that low resistance was not such a material factor as I had thought, but we did achieve a relative immunity from trouble, as the causes became better understood.

I should also like to mention a little matter which arose a short time ago in connexion with foundry fettling. I have seen films which seem to show that the products of grinding—that is, the particles which are thrown off by an ordinary grinding wheel applied to ferrous material—probably divide. The larger particles describe an elliptical path and fall to the ground, whereas the powder seems to go off at right angles from the fettling wheel. These grinding processes, of course, involve the occupiers of factories in expensive extraction plants to reduce the risk of silicosis to the workpeople. I have heard it said that if these particles, which are no doubt electrified, and all possess the same sign, so that they repel each other, could be married together in some way, so that the finely-divided powder which goes off at right angles could be married to the big particles which follow their independent path, we should achieve something which would make it less necessary to have such comprehensive ventilation and extraction. I remember Major Gill telling me about his experiments with particles of sand sliding down a chute and how he managed to change the sign of electrification at will by stretching wires along the top of the chute. Perhaps this principle could be used to change the sign of either the big particles or the dust and thus we could succeed in marrying them.

I should like to say something about aircraft. During the war, we had trouble due to the difficulty of emptying petrol tanks. When damaged self-sealing types of petrol tank were brought in it was necessary to remove them from the aircraft, drain, and return them to the works for repairs. That sounds simple enough, but the actual job of draining such an aircraft petrol tank, which is of a peculiar shape and fitted with internal baffles is difficult, and we found that in many cases trouble arose from the petrol left in the tank. When the soft, spongy, rubber material used for sealing was being torn off the petrol tanks, there was often sparking, and if it was anywhere near the filling orifice or the shot holes it was possible that a major explosion would occur. There was, in fact, loss of life.

In dealing with this matter we had the assistance once more of the University of Birmingham, and also of a commercial research organization. The practice adopted in repair was that of standing the tanks up in X-chocks and tearing off the rubber. With the repairs being done day after day a good deal of the rubber solution was spilt and spread all over the chocks and the floor. The petrol tanks were consequently very well insulated, and electrification was shown to be easily possible. It was a serious matter, which we overcame to some extent by putting metal covers on the chocks and trying to keep them clean. Gradually the explosions did lessen.

I remember in the early 1920s being asked to look into a case where one of the road tankers which were then being fitted with rubber tyres for the first time exploded during filling at the refinery. It was quite obvious that what was happening was that the tank itself was insulated by the rubber tyres, and the filling pipe had been taken into a manhole 12 in. in diameter, the filling pipe being only 3 in. in diameter. One can see the type of thing that can happen. If the filling pipe is put in the centre of the manhole it will be too far away to spark to the rim of the manhole. On a day, however, when the pipe is, say, only $\frac{1}{2}$ in. away from the rim and the petrol is pumped into the tank, air comes out and you get the right mixture at the orifice to be ready for the incendiary spark when it jumps. In that first case two men were killed. We found that it was possible to overcome the difficulty by bonding between the filling pipe and the tank, a practice which is now well established.

You will have heard, no doubt, of the recent disastrous fire at Avonmouth. There a tank had been relegated to the storage of heavy fuel, and the filling pipe ended short at the top, whereas in tanks designed for the storage of light spirit it is customary, and good practice, to carry the filling pipe right down to the bottom, so that the inlet gush is quickly submerged. The operation of observing the level of oil pumped from a ship into the shore tank was being undertaken, and an attendant lowered a steel tape into the tank from the manhole in order to measure the depth of oil already admitted. It has been borne in on me again and again during my long life that these troubles occur as a result of coincidences. They take place only if a number of conditions are simultaneously fulfilled. If only three or four conditions are fulfilled nothing happens, but when, say, all five—if five are necessary—coincide you get trouble. It makes one realize to what an extent safety generally is dependent on coincidences not happening. We did not expect the heavy fuel to have been contaminated in the voyage by a mixture of light spirit, which is highly inflammable, but that happened, and thus the turbulence and evaporation associated with the filling of the mixture into the tank at Avonmouth produced an inflammable mixture which was ignited by an incendiary spark resulting from electrification which was probably equalized when the man lowered the steel tape into the tank.

I should like to touch briefly on electrification of cinematograph films. Some of the fires which occurred in cinematograph theatres were thought to be due to static which ignited the highly inflammable celluloid. With the assistance of the Electrical Research Association we bored holes in cinematograph films by means of big sparks from a Wimshurst electric machine but we never succeeded in setting an inch of the film alight. I was quite at a loss to understand why the fires continued from time to time until I went to a cinema one day when they were getting the film ready for the Sunday show. The film shown on Sunday is not always the best and newest. In order to prepare it the operators sometimes have to make as many as ten or more joints in a spool, because the film has broken at the theatre where it was last exhibited, and the operator there has left it to the next man to make the joints. The next man does it as quickly as he can, and the cement used to make the joints usually includes some kind of solvent which is inflammable. If the film is spooled up quickly after the joints are made there will be vapour present as well as celluloid, and electrification is possible. The operator often steadies the film into the spool box with his fingers while moving the handle round, and so the sparking, if it occurs, ignites the vapour from the solvent and jointing material and that sets fire to the film.

We now come to accidents in hospitals. A good deal of work has been done to counter the distressing, but fortunately rare, accidents in hospitals due to the ignition of inflammable anaesthetics, usually ether and cyclopropane. About 25 years

ago I was asked to offer an opinion on the cause of an explosion in the anaesthetic room of a large London hospital. That was my first introduction to this particular risk and I obtained the assistance of the National Physical Laboratory. We reached the conclusion that this was a case where the patient's trolley or stretcher, which runs on rubber tyres, had been electrified by movement of the dry, hot blankets, which the nurse was moving at the time that the explosion occurred. I am glad that papers on the subject of static electrification in hospital theatres are included in this conference. (See pages S 87 and S 92.)

During the war, another problem arose when explosions occurred in ammunition-filling factories where they were making sensitive detonators. I learnt that it was possible to set off a lead azide detonator at 7 V with a capacity of about 15 μF. That needs qualifications with regard to series resistance and so on, but it shows the kind of problem with which those concerned had to grapple. We tried the use of conductive rubber on the floor, and we tried to get some conductive linoleum. In some cases the departments were washed out with water hoses once every shift, as a means of humidification to prevent personal electrification caused by movement. Some places introduced what I called an American electrocution chair, because as the people who worked in these small departments were admitted they were required to sit in this chair, which was furnished with electrodes for the feet and hands, with measuring instruments. Unless the overall conductivity shown was such as to allow the passage of more than 70 μA they were told to run round the factory and have a cup of coffee before trying again, and after that they usually got through. On a Monday morning there were more rejects than on a Friday, presumably because they were wearing newly washed clothes on the Monday.

I want to refer to the question of spark incendivity, which I do not understand. If you put a series resistance of a certain value in circuit with a static spark you may increase its incendivity. I first came across this when Dr. F. T. Farmer produced a formula for series resistance which I saw about 1941 or 1942, and it seems to me to complicate the risk greatly. For instance, I think it was Professor E. G. Cox who said in a paper that ignition of a starch dust cloud may require a condenser spark discharge of up to 100 joules, but with a suitable resistance in series 0·2 joule will suffice. If we have to reckon with that wide variation in spark incendivity, it seems to me that we have a set of very unpredictable factors in the everyday problem. I express this opinion with great diffidence and obvious ignorance, but it seems to me that the problem is much more difficult of solution than it appeared to be when I first tackled it 30 years ago and suggested earthing everything. There are evidently far more complications, but even so, various people are achieving success in dealing with individual problems, for example an attempt is now being made in hospital operating theatres to supplement conductive rubber by terrazzo floors, which have been rendered semi-conductive by mixing them with acetylene black.

There remains, however, a considerable general problem in connexion with risks arising from static electricity.

The practical estimation of electrostatic hazards*

By W. Fordham Cooper, B.Sc., M.I.E.E., H.M. Electrical Inspector of Factories

The paper deals with experimental procedure and methods of calculation rather than particular results.

An attempt is made to provide a basis for the quantitative study of electrostatic hazards met in industry and attention is drawn to several elementary but important details which are frequently overlooked. It is shown that a material cannot retain a bulk charge unless its resistivity exceeds about 10^{11} Ω cm and that vessels will not remain significantly charged unless they are very highly insulated. This depends very largely on the relative humidity of the air, and for this reason experimental work and measurements may present considerable difficulties in the British Isles.

Problems of static electrification can be stated conveniently by a generalization of Maxwell's coefficients; examples are given, including a discussion of the interpretation of the indications of certain instruments, and the surface potential of a charged liquid in an earthed container—such as a bowl or a storage tank. The notation is suitable for other electrostatic problems as well as those considered in this paper.

1. List of symbols

C = capacitance
H = relative humidity (%)
I = current
K = dielectric constant (specific inductive capacity or permitivity)
p_{ab}, $\overline{p_{ab}}$, p'_{ab}, $\dot{p}_{ab}$ = potential coefficients
Q = electric charge
R = electrical resistance
ρ = electrical resistivity
S = volume density of electric charge
V = electrical potential or potential difference
X = electrical intensity or force.

* Any opinions expressed are those of the author personally and do not necessarily represent those of his department.

2. Introduction

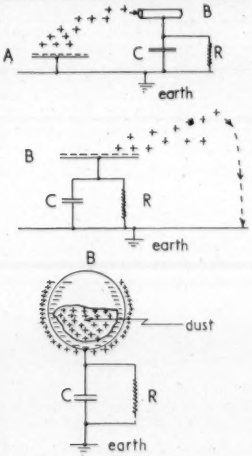
Very large electrical charges are nearly always produced when materials are handled or manipulated, but they are not often observed because in most circumstances they immediately leak away or are neutralized. They are a nuisance in many industries and where inflammable vapours or dusts are present there may be considerable danger, but the writer assumes that other contributors will deal with these matters in more detail. During the last twenty years he has investigated a substantial number of fires and explosions attributed to "static" and advised on experimental investigations and on precautions to be taken where electrification was suspected or thought possible. During this period he has collected reports and publications from a variety of sources but has found very few that give sufficient data for any calculations to be made. In most cases essential variables

had either not been recorded or were clearly not under control.

The present paper is an attempt to indicate the controlling conditions and the precautions which must be taken to ensure that observations have something more than qualitative value. Some parts of the paper are elementary but they are included because they deal with matters which are frequently overlooked, even by eminent physicists when they advise on this matter.

3. PRODUCTION AND DISSIPATION OF CHARGES

In nearly all electrification problems positive and negative charges are separated by some mechanism A and charged material is then transferred to a container B (Fig. 1), or it is dissipated (Fig. 2). A variation is for the material to be transported through B on a conveyor belt, as suspended dust in a duct or in some other way. When a charge is within a metal container or duct (Fig. 3) it induces equal and opposite charges on it. If the container is insulated from earth and the material is in contact with the container, the bulk charge will leak to the surface and start to neutralize the inner induced charge, but the outer charge will remain unchanged until it is itself neutralized by leakage conduction from earth. If the material is then transferred to another container it will carry its own remaining bulk charge with it, but will usually leave a residual charge on B because the inner and outer induced charges have not been neutralized to the same extent. The effective charge of an insulated container is (bulk



Figs. 1, 2 and 3. Production, induction and dissipation of static charges

charge − inner induced charge + outer induced charge) and it will build up according to the law

$$Q = (1/\beta)I_t[1 - \exp(-\beta t)], \text{ where } \beta = 1/R_lC \qquad (1)$$

Equilibrium is reached when

$$Q = I_tR_lC \text{ or } V = I_tR_l \qquad (2)$$

where I_t is the charging or transport current, R_l the leakage resistance and C the capacitance. This last equation was the basis of the only satisfactory large-scale series of experiments on the electrification of liquids with which the writer is familiar (Mackeown and Wouk). V, I_t and R_l were all accurately measured, but the instrumental difficulties were considerable and for reasons discussed below it is doubtful if the experiment, as carried out, would have been successful in this country.

If the supply is intermittent, being on for periods t_1 and off for periods t_2 so that $t_1 + t_2 = \tau$, then the limiting charge is $Q = I_t[1 - \exp(-\beta t_1)]/[1 - \exp(-\beta\tau)]\beta$.

When the supply ceases the charge leaks away or is neutralized according to the equation

$$Q_t = Q_0 \exp(-\beta t) \qquad (3)$$

These results are particular examples of the relaxation rules discussed in the next section.

4. RELAXATION, CRITICAL RESISTIVITY AND EARTHING

It is well established that isolated bulk charges cannot be produced *within* a substance but only conveyed there by mechanically "mixing in" surface charges. A surface where ρ is discontinuous may become polarized by the flow of current across it but the charges will recombine when the current ceases. It is unlikely that effective bulk charges will arise from this source; they are the result of other phenomena. Once established they decay according to the relaxation law

$$S_t = S_0 \exp(-4\pi t/K\rho) = S_0 \exp(-\gamma t), \text{ say, in e.s.u.} \qquad (4)$$

which is independent of the geometry of the situation and cannot be altered or interfered with.

From this (using a slide rule) we obtain the following approximate results:—

$1/\gamma$	$\exp(-\gamma t)$ *after 1 sec*	*after 2 sec*
0·1	0·00005	$2{\cdot}06 \times 10^{-10}$
0·2	0·0067	$4{\cdot}5 \times 10^{-5}$
0·3	0·036	$1{\cdot}3 \times 10^{-3}$
0·4	0·082	$6{\cdot}7 \times 10^{-3}$
0·5	0·135	0·018
0·6	0·19	0·036
1·0	0·37	0·135
5·0	0·82	0·67

It is clear that S_t is very sensitive to changes in $1/\gamma$ from 0·1 to 1·0 and 0·2 may be taken as a convenient line of demarcation; when ρ is expressed in *practical* (Ω cm) units the result may be expressed as follows:—

If the bulk resistivity of a charged mass exceeds 10^{11} Ω *cm then charges can be observed, but if it is less than this value they will leak away very quickly, in fact if* ρ *is less than* 10^9 *the material is virtually a perfect conductor for the present purpose.*

It follows that when ρ is not very high, charges will be neutralized quickly or will become distributed at the surface in the manner necessary to render it an equipotential, as for a conductor, and large sparks may be obtained from it. Sparks from the surface when ρ is large can only discharge electricity in the immediate neighbourhood and are not nearly so dangerous.

A similar rule holds for imperfectly insulated charged conductors (or bins enclosing charged material)

$$Q_t = Q_0 \exp(-\beta t) \qquad \text{(3 repeated)}$$

as stated in Section 3 and the values calculated for $1/\gamma$ above, apply to $1/\beta$, but the equation is here expressed in practical units, Q being in coulombs and $\beta = 1/R_lC$ in ohms and farads, and for a charge to persist R_lC should exceed approx. 0·2. Since the capacitance to earth of many industrial vessels is of the order of 200 to 300 $\mu\mu$F it is clear that charges will not be observable unless R exceeds approx. $10^9\ \Omega$ (1000 megohms).

Alternatively, we may note that charging currents are often less than 10^{-8} A and unless R exceeds approx. $10^{10}\ \Omega$, dangerous voltages cannot arise.

The result is not so definite as that relating to the relaxation of bulk charges, and its similarity may be a little misleading, but it is clear that a very high resistance may be present in the earth path without rapid discharge being prevented. The advantage of heavy earth bonds lies in their mechanical strength and obviousness. They are easy to maintain and have a valuable psychological effect. As indicated in Section 13, however, there are some situations in which they do not ensure safety.

The reason for the recurrence of numbers such as 10^{10} is that the *natural units* for electrostatic phenomena are e.s.u. and 1 stat-ohm is roughly $10^{12}\ \Omega$.

5. BULK AND SURFACE RESISTANCE, HUMIDITY

The bulk resistivity ρ of many substances depends very largely on the adsorbed moisture content and they will only retain charges when they have been freshly and thoroughly dried. The surface resistance of many insulators is even more sensitive to changes in atmospheric humidity, as is illustrated by Table 1. The resistivity of hard surfaces varies very rapidly with the humidity of the air, but there may be a considerable time lag in bulk resistivity. Should a piece of apparatus be colder than the surrounding air, moisture will condense on it and its insulation resistance will collapse. If it is warmer it will tend to dry out, and its resistance will become high.

Table 1. *Surface resistance of a sample of glass*
(Thornton and others)

Relative humidity $H(\%)$	*Relative resistance*
100	1
80	4
70	30
60	800
50	30 000
40	6 000 000

Another matter of importance is the difference of temperature between the inside and outside of buildings, particularly in winter. Air is usually drawn from the outside and warmed, and although its water vapour content may remain substantially unchanged the relative humidity will be very greatly reduced. For example, air with 60% humidity at 50° F when warmed to 65° F will have its humidity reduced to 40%* and this might well cause a 10 000-fold increase in the insulation resistance of apparatus; for this reason winter conditions favour the accumulation of indoor static charges; they also favour outdoor electrification, for in frosty conditions there may be no conducting surface film at all. These conclusions are supported by Fig. 4.

The importance of the sensitivity of the surface resistance of insulators to temperature and humidity is illustrated by the large scale experiments of Blactin and Robinson on the electrification of coal dust clouds. They obtained high voltages so long as the sun was shining, but so soon as it went behind a cloud the voltage disappeared completely.

The writer apologizes for labouring matters which may seem obvious and elementary, but he has found on more than one occasion that they provided a sufficient explanation of results which investigators had found unexpected and puzzling.

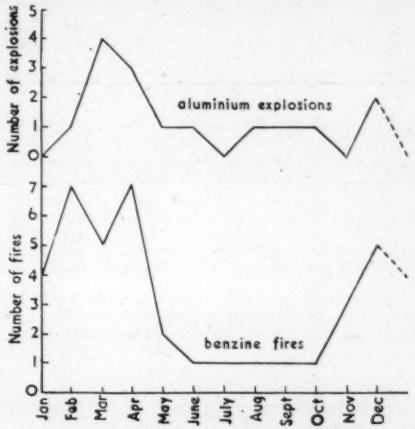


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Fig. 4. Incidence of aluminium dust explosions and benzine fires [RICHTER]

Control of bulk resistivity (if necessary by routine sampling) and humidification are the best measures for suppressing charges when they are applicable. Sometimes the cure when the electrification is a nuisance rather than a danger may be ridiculously simple, such as removing a machine away from a heater or boiling a kettle.

6. METAL POWDERS

Metal powders often have a high effective resistivity owing to surface films of oxide, grease or adsorbed gas, but the writer has found this insufficient to prevent the rapid relaxation of bulk charges. On the other hand, aggregates of such powders when forming the "dielectric" of a condenser, or otherwise forming part of the leakage path to earth from charged conductors, may have sufficient resistance to make the discharge to earth very slow. They are often, however, subject to coherer effect and will not as a rule withstand a potential gradient sufficient to cause internal sparking. They therefore seem unlikely to be ignited by the leakage of static charges *through* them, though even quite small "power leakage" might cause dangerous heating. Powders might perhaps be ignited by sparks between containers, etc. The subject is important because explosions of metal powders have often occurred and they are sometimes very violent and the cause of these explosions has not so far been satisfactorily explained.

* Such calculations are most conveniently made with the aid of the hygrometric charts provided in text books on ventilation.

7. CONDUCT OF INVESTIGATIONS

Mere observations of sparks or even measurements of voltage are of little value since they depend very largely on the accidents of the geometry of the equipment and the leakage resistance, and give little information on the fundamental process of electrification. It follows from the analysis in Section 4 that the total charge generated can only be measured directly if the charged material is collected in a container with an exceedingly high insulation resistance, which should be of the order of $10^{20}\ \Omega$. The internal leakage of commercial measuring instruments may easily be sufficient to vitiate the results and the writer found that it was quite impossible to carry out some laboratory experiments in damp weather. Some form of air conditioning may prove essential.

It is also doubtful how far small-scale results on a process such as sieving are truly representative of industrial conditions; large-scale experiments can be made on the basis of equation (2) which gives a simple relation between the rate of generation and the stable voltage and leakage resistance. A difficulty arises in this country from instability due to changes in surface leakage which is very sensitive to variation of temperature and the humidity of the air. It is therefore necessary to measure the leakage resistance from time to time during an experiment and this requires special instruments because of its very high value.

In their work on petroleum, Mackeown and Wouk (Fig. 5) used an insulated container earthed through an ammeter and measured the current as it leaked away. The container was a tank wagon with its tyres resting on blocks of wood boiled in paraffin, and no doubt the dry air of California was a considerable help in maintaining the insulation resistance at a high and constant level. As it was necessary to measure

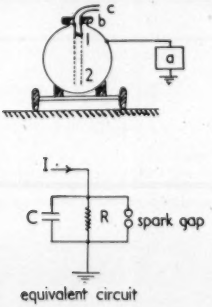

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Fig. 5. Measurement of current due to flow of petroleum spirit (one of several arrangements used by MACKEOWN and WOUK)

currents of the order of 10^{-8} A an electronic instrument was used and in our less favourable climate we should be left with some doubt whether its impedance was sufficiently low to prevent errors caused by parallel leakage paths to earth.

In work on the electrification of liquids the requirements of dynamical similarity must be observed (see the companion paper, *The electrification of fluids in motion*, see page S 11). It is also important that the apparatus used should be clearly described in reporting the results and that the dimensions of the part of the equipment causing the separation of the charges should be given, so that any scale effect can be investigated as in normal hydrodynamic research. The method of measurement and electrical constants such as the leakage resistance and the capacitance (or potential coefficients) of the receiver should also be stated.

8. INSTRUMENTS

When engineers (or physicists) first attempt to investigate practical examples of static electrification they nearly always have trouble with their instruments and frequently obtain spurious results. Ordinary commercial instruments and most laboratory equipment are unsuitable for this work. The following equipment is suggested:—

(*a*) Ammeters reading down to about 10^{-8} or 10^{-10} A which should have comparatively low impedance to prevent errors due to parallel leakage.

(*b*) Voltmeters with very high internal resistance and a very high standard of insulation to prevent the collapse of the potential to be measured.

(*c*) Ohm meters capable of reading from approx. 10^{9} to 10^{15} or $10^{20}\ \Omega$. These instruments must often be used in danger areas and should therefore be "intrinsically safe." (See B.S.S. No. 1259/1945.)

These requirements are most easily met by electronic instruments or by quadrant electrometers, provided special precautions are taken with the insulation. In industrial investigations one of the most important and difficult values to determine is the resistivity ρ (or alternatively $K\rho$) of materials since the critical range is in the neighbourhood of 10^{9}–$10^{15}\ \Omega$ cm. Various electronic and other testing cells have been described for liquid dielectrics and these may be made in a portable form. Alternative methods are available such as observing the rate of decay of charge on a condenser with a quadrant electrometer, the material under test forming the dielectric; or comparing such a condenser with an air condenser by means of an a.c. bridge circuit. Whatever method is adopted it is doubtful if reliable results can be obtained except in a laboratory and in many localities air conditioning may be necessary. In one set of experiments the writer found that leakage within a quadrant electrometer completely masked the decrement being measured.

9. CALCULATIONS

The writer has found it safest to do all *theoretical* work in C.G.S. electrostatic units and then to convert the formulae to practical units. Nearly all the important mathematical investigations which must be consulted are in C.G.S. units and the formulae are free from high powers of 10 which are a nuisance in analytical work. It is common American practice to refer to the electrostatic system of units as stat volts, stat farads, etc., and a unit is required for potential coefficients; these are quoted as reciprocal farads (r.f.) or reciprocal stat farads (r.s.f.) and it may be noted that 1 stat farad = 1 micro-micro farad ($\mu\mu$F) approximately. The process of generating and dispersing electrostatic charges under practical conditions is always unstable and for that reason only rough calculations are justified. In fact we are only interested in the order of magnitude ($\log_{10}$) of the result, which may serve as an indication of the probability of danger and though in some cases exact formal solutions of problems could be obtained it is usually a waste of time. The two quantities which it is most helpful to calculate are potentials and potential gradients. These are considered in the following sections.

10. POTENTIAL GRADIENT

It is sometimes useful to estimate the potential gradient near the surface of a bulk charge. The following rule, based on a consideration of theoretical values for various geometrical forms, has been found sufficient

$$X = na(\pi S/K) \text{ in e.s.u.} \quad (5)$$

where n is a constant varying from 0·66 for a compact mass to 2·0 for a thin "slice" and a is the least distance through the mass near the centre of gravity, bumps and hollows being disregarded.

Because the process of electrification is usually very unstable only the roughest estimates are worth while and, in fact, $X \simeq aS$ will be sufficient to determine the order of magnitude. It is never possible to say whether or not a spark will occur in a doubtful case, but it is sometimes possible to state that there is some possibility of a spark and in other cases that a spark is impossible. For example, it does not seem likely that internal self-induced sparks would occur in a dust cloud for any probable density of cloud or degree of electrification unless it approached at least the size of a small house. More accurate data for such an estimation would be valuable. The density of charge in the discharge from a chute, however, is likely to be much higher (Fig. 6) and more data is desirable.

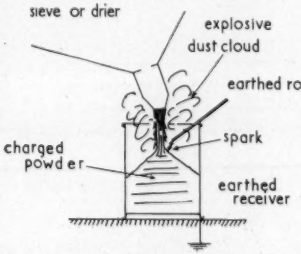

Fig. 6. Dangerous spark to surface of charged material inside *earthed* container

11. POTENTIALS COEFFICIENTS

The calculation of potentials in the presence of both conductors and charged masses is often difficult and a convenient notation is valuable as a guide to stating the problems clearly and concisely. The writer has found the following generalizations of Maxwell's potential coefficients helpful:

(*a*) A conductor (n) in the presence of other charged conductors is at an absolute potential given by

$$V_n = p_{nn}Q_n + p_{1n}Q_1 + p_{2n}Q_2, \text{ etc.} \quad (6)$$

The p's are potential coefficients measured in reciprocal farads (r.f.) or reciprocal stat farads (r.s.f.) and the Q's are the charges on the conductors, and $p_{nm} = p_{mn}$.

(*b*) A conductor (n) in the presence of bulk charges is at a potential given by

$$V_n = \bar{p}_{1n}Q_1 + \bar{p}_{2n}Q_2, \text{ etc.} \quad (7)$$

(*c*) The potential *at a point* (n) not on a conductor but in the presence of charged conductors is given by

$$V_n = p'_{1n}Q_1 + p'_{2n}Q_2, \text{ etc.} \quad (8)$$

(*d*) The potential *at a point* (n) not on a conductor but in the presence of bulk charges is given by

$$V_n = p'_{1n}Q_1 + p''_{2n}Q_2, \text{ etc.} \quad (9)$$

It is not essential to use a different notation for the four coefficients, but it is on the whole convenient. A short note on the estimation of these coefficients is given in the Appendix.

12. ELECTROSTATIC SCREENING

As a simple illustration we may consider the effect of electrostatic screening from bulk charges. The potential of a conductor b due to bulk charge Q_a is (in isolation)

$$V_b = Q_a\bar{p}_{ab}$$

In the presence of an earthed conductor c (see Appendix).

$$V_b = Q_a(\bar{p}_{ab} - \bar{p}_{ac}p_{bc}/p_{cc}) \quad (10)$$

This has a bearing on the instruments sometimes used in "field measurements" and is considered below (Section 14).

If c is nearer than Q_a to b, then complete enclosure is not necessary for substantial screening, but it is shown in Section 13 that screening may be of limited value for our purpose.

13. POTENTIAL INSIDE A VESSEL CONTAINING CHARGED LIQUID (OR DUST)

This provides another straightforward and important application of potential coefficients; let

Q_l = the charge on the liquid.
Q_v = the net charge on the vessel.

Then $Q_v/Q_l = -\bar{p}_{lv}/p_{vv}$.

V_n = potential at point n in liquid.
V_v = potential of the vessel which is zero when it is earthed.

The potential at a point n in the vessel is given by

$$V_n = (p'_{ln} - p'_{vn}\bar{p}_{lv}/p_{vv})Q_l \quad (11)$$

An important instance is a hemispherical bowl radius r filled with charged liquid, the dielectric coefficient of which will be taken as unity. Then it can be shown that $p'_{ln} = 3/2r$ if n is at the centre of the free surface, $p'_{vn} = 1/r$ and $\bar{p}_{lv}/p_{vv}$ lies between 7/8 and 1·0.

Thus we see that if the liquid is in an unearthed or insulated bowl carrying no charge the potential at n would be $V_n = (1{\cdot}5)Q/r$, while the effect of earthing is only to reduce this to between $(5/8)Q/r$ and $(1/2)Q/r$. If a metal rod or paddle or one's hand is brought near the liquid surface a spark may occur in spite of the bowl being earthed and a number of fires appear to have been caused in this way in home dry cleaning and the mixing of rubber solution, etc.

The following is a typical numerical example. Petrol was run into a bowl (about 20 cm diameter) and when it was picked up it burst into flames. Assuming that it held a gallon, the maximum possible charge was estimated to be 2250 stat coulombs (from the data given in the companion paper). Then if K is taken as unity, as only approximate results are required,

$V = Q/2r$ (approx.), see above,
= 100 stat volts (approx.),
= 30000 volts (approx.) near the centre,

assuming that there was *no* relaxation. It is clear that even if ρ was not very high a spark could easily occur, but other calculations show that the energy would not be very high and ignition would not be certain. The writer has applied similar analysis to the potential gradient across the surface of petroleum in a large storage tank at a dock.

There is a matter here which can easily be overlooked. When a material which has a high resistivity is collected in a metal vessel it may be dangerous to bring an earthed conductor or semi-conductor near its surface, whether the vessel is open or closed, earthed or unearthed, while if the material has a resistivity below about $10^7\ \Omega$ cm it behaves as a conductor and is at zero potential if the vessel is earthed, but may be at the same high potential as the vessel if the latter is unearthed.

14. POTENTIAL FIELD MEASUREMENTS

Experiments have from time to time been reported in which measurements were made of the "voltage" produced by electrification by what seem to have been invalid methods. It is possible to measure the potential of a charged conductor if an instrument—such as a quadrant electrometer—is available which has a sufficiently high internal resistance and a sufficiently low capacitance, but to determine the potential of a charged insulating surface or at a point in space is entirely different.

When an uncharged and insulated conductor is introduced into a field it is at a potential which can be calculated from the potential coefficients if these are known, but its presence distorts the field locally. Thus if we do not wish to disturb the field we are measuring, we may try to find the potential of a search electrode which is small compared with the "scale" of its surroundings. It is impossible to measure the potential of such an electrode, e.g. a sphere, without connecting it to an instrument which will itself have a capacity. We may represent this roughly by another sphere and we thus have a compound conductor consisting of two spheres connected by a wire. This conductor will, however, assume a potential corresponding to the "undisturbed" field at some point along the wire depending on the relative capacity of the two spheres. The reading will *not* give the undisturbed potential at the search electrode, even approximately, unless its capacity is large compared with that of the instrument, which may be incompatible with the requirement that its size must be small so as not to disturb the field. (Fortunately it may be shown that the distortion due to the fine wire is very small and local.)

If a very small search electrode is used, it will not distort the field but some means must be found of bringing it to the undisturbed potential at any required point, which can be done if it is made to give up or receive charge until the whole compound conductor is at this potential and it is necessary to render the air conducting in the immediate vicinity of the probe, which may be achieved by placing a very small amount of radioactive material on the tip. Meteorologists frequently use a small flame but this is hardly suitable in inflammable surroundings or in an explosive works. The instrument capacity should still be kept small to limit the time of charge and to ensure that it cannot be the source of an incendiary spark. The probe and wire should be insulated except at the tip, with a high grade, non-hygroscopic material and for this polystyrene seems suitable and it could also be used for instrument bushings. The importance of surface leakage and moisture have been explained.

Sometimes instruments are used which consist of some sort of electroscope say (*b*) inside an earthed shield (*c*) with an open window which is "aimed" at a charged surface (*a*) from a distance away. The potential induced on the detecting member as given by equation (10) above is $V_b = Q_a(p_{ab} - \bar{p}_{ac}p_{cb}/p_{cc})$ in which p_{cb} and p_{cc} are fixed by the design of the instrument, but $\bar{p}_{ab}$ and $\bar{p}_{ac}$ depend not only on the distance of the instrument from *a* but on the complete set-up of the machine or apparatus producing the charges, and on its relation to earth and to other earthed metal which all affect the field and gradient *at the instrument*, on which the reading actually depends. Such an instrument will give an indication of the presence of significant charges in its vicinity, but the quantitative significance of its readings is uncertain.

15. EXPLOSION RISKS

The static spark energy necessary to ignite a gas or vapour is very small and varies from about 0·0005 joule for benzine to 0·01 for dioxine. For dust clouds it varies from 0·1 to 2·5 joules and is occasionally higher. The charges obtained electrostatically, however, are often very small and ignition may not occur even at very high voltages, but it is safest to assume that if there is a spark there is danger. It is also known that corona or a brush discharge of a few milliamperes will ignite hydrogen and coal gas.

It is probable that explosions are often prevented by the vapour concentration falling outside the explosive limits, a comprehensive table of which is given by Coward and Jones. The range for many solvents is quite narrow, and if they are very volatile and have a low flash point the vapour concentration near the liquid surface may well be above the upper explosive limit. This may be one reason why explosions in petroleum storage tanks are not more frequent. The range for some vapours, however, is wide, e.g. carbon disulphide 1·25 to 50% and ethyl ether 1·9 to 48%. These are obviously much more dangerous to handle.

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APPENDIX

Note on potential coefficients

Values for potential coefficients can be obtained from the older works on electrostatics and gravitation; the writer has used Jeans' *Electricity and Magnetism* and Gray's *Treatise on Physics*, Vol. 1, but the most useful source has been Routh's *Analytical Statics*. For the most part it is possible to obtain accurate values only for such bodies as ellipsoids, but properly applied these can be made to give approximate values for many problems.

Values for p_{nm} and p'_{nm} for irregular bodies can easily be

obtained in an electrolytic tank and if low voltage a.c. is used no special precautions are necessary to obtain results of sufficient accuracy and the apparatus can be calibrated by finding p_{nn} for a unit sphere.

Values of p'_{nm} are fairly easily estimated by numerical integration and it can be shown that $\bar{p}_{ab}$ is the mean value of p'_{ab} for conductor a taken over the volume occupied by the bulk charge b.

Potential coefficients are not the reciprocals of capacitance. Although they are measured in reciprocal farads the relation is more complicated. For example, the capacitance between two conductors a and b is $1/(p_{aa} - 2p_{ab} + p_{bb})$.

The following example from the paper illustrates the manipulation of these terms.

The potentials of two conductors b and c in the presence of a bulk charge Q_a are

$$V_c = Q_a\bar{p}_{ac} + Q_c p_{cc} + Q_b p_{cb}$$
$$V_b = Q_a\bar{p}_{ab} + Q_c p_{cb} + Q_b p_{bb}$$

If $Q_b = 0$ and $V_c = 0$, i.e. b is insulated and uncharged and c is earthed then

$$Q_c = -\,Q_a\bar{p}_{ac}/p_{cc}$$
$$V_b = Q_a(\bar{p}_{ab} - p_{cb}\bar{p}_{ac}/p_{cc})$$

Equation (11) is obtained in a similar way.

DISCUSSION

Dr. T. B. Rymer: Mr. Cooper refers to the possibility of a static spark setting fire to charged petrol contained in an earthed metal bowl and (in Fig. 6) to the occurrence of a spark to the surface of charged dust in an earthed container. It is difficult to see how such a spark can occur in the case of a homogeneous dielectric. If the specific resistance of the dielectric be less than $10^{11}\ \Omega$ cm no large charge can exist in or on the dielectric if it is in contact with an earthed container; on the other hand, such a high value for the specific resistance will severely limit the current flow from the dielectric and therefore inhibit a spark discharge.

Consider an isolated spherical mass of dielectric of radius R and having a total charge Q uniformly distributed throughout its volume. This volume charge will gradually diffuse to the surface, where it will accumulate as a surface charge. If τ be the relaxation time of the dielectric, the total current reaching the surface will be Q/τ and the current density will be $Q/4\pi R^2\tau$. The order of magnitude of the current density in a discharge to an earthed metal rod brought up to a point on the surface of the dielectric cannot be very different from this. To take an example similar to one given by the author; consider a sphere of dielectric of radius 10 cm and having a uniformly distributed charge of 2000 e.s.u. If we assume a relaxation time of 10 sec, the current in a spark channel of 1 mm^2 cross-section would be only 5×10^{-13} A; too small to sustain a spark. For a spark to occur, it appears to be necessary to have an inhomogeneous dielectric. One possibility is that there may be a mass of relatively low resistivity dielectric surrounded by material of higher resistivity which insulates it from the container. The spark then occurs by the discharge of this low resistivity mass, which acts like a conductor. Alternatively, the surface layer of the dielectric may be of low resistivity. This layer will become charged by the diffusion outwards of the volume charge, and the spark is caused by the discharge of this surface layer as a charged conductor. The second explanation would, of course, require that the high surface conductivity should not extend over the whole surface, otherwise the earthing of a single point of the surface would remove all the accumulated surface charge on the dielectric.

Dr. E. C. Craven: As one connected with the large scale manufacture of inflammable solvents I cannot accept Mr. Cooper's view that since these solvents have a specific resistance less than $10^9\ \Omega$ cm we need not fear ignition from static effects. I conceive it possible that even a moderately conducting liquid could in some way acquire a charge if in an insulating container, and there would be a discharge when this liquid approached an earthed conductor.

Author's reply: Dr. Craven questions the reliability of the $10^9\ \Omega$ cm rule for the effective dissipation of charges. There is, of course, no sharp dividing line, but, as stated in my paper on the electrification of fluids in motion, Hartshorn and Ward could obtain no noticeable charge in dry cleaning below 10^{11} which agrees with earlier results by Richter and similar results have been obtained for electrification by flow. Since the conference I have heard from Mr. Gill of the Clarendon Laboratory that below 10^9 he could not detect charges in petrol.

A charge may be obtained if the liquid is broken up into drops and is collected in an insulated vessel, but if the resistivity is below about $10^9\ \Omega$ cm it will almost instantaneously pass to the surface and charges may be eliminated by substituting an earthed vessel. No appreciable charge would, I think, collect on the free surface because this would in effect form one plate of a condenser, the other plate being the vessel, and the relaxation time of this would be of the same order as that for the bulk charge.

Dr. Rymer questions the possibility of a spark discharge to the surface of an insulating medium carrying a bulk charge. This was briefly considered in the original draft of the paper, but was one of the parts cut out at the request of the referees in order to reduce it to a more convenient length. What happens is, I believe, somewhat as follows; when the electrical stress exceeds the breakdown strength of the air an "electron avalanche" occurs in the normal way just as for a conductor but, either the electron stream spreads over the surface, if that is positive, much as a small jet of water will spread over an impenetrable surface, or electrons are, as it were, sucked up from the surrounding surface if it is negative. Whether this develops into a visible or incendiary spark depends on two things; the space or surface charge on the conductor will in time become sufficient to reduce the electric field below the sparking potential, and as the "spot" spreads, the electrical intensity at the edge of the circle will become too low to prevent further spread. The time which must elapse before a further discharge will depend on the relaxation constant of the material. An actual visible spark may consist of a rapid sequence of such discharges or a number occurring in parallel from closely adjacent areas. Since this paper was written, confirmation of this suggestion has been given in two papers* read at the Symposium on Insulating Materials at the Institution of Electrical Engineers in March of this year.

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Electrostatic eliminators in the textile industry

By P. S. H. Henry, Ph.D., F.Inst.P., The British Cotton Industry Research Association, Manchester

The occurrence of static electricity in the textile industry, and the ways in which it interferes with production, are briefly described. The general principles of its dissipation are discussed, with special emphasis on the time factor. Brief descriptions are given of the various types of electrostatic eliminator, both electric and radioactive, used in the textile industry, with references to the commercial apparatus.

Artificial fibres of a highly insulating nature are coming into increasing use in the textile industry. At present these are mainly cellulose acetate and nylon, but others will soon be on the market. All these materials develop a charge when passed through any machine (except in wet processes), and are liable to give trouble in consequence. The charges are most intense when the material has been subject to rubbing, as when a yarn passes through a guide, but they may be a nuisance even when contact with the machine has occurred without obvious rubbing, e.g. during passage between rollers. The amount and sign of the charge may vary with, among other things, the nature of the surface with which the textile has been in contact, but a substance which can be used for yarn guides and will not give rise to static on the yarn has not yet been discovered, so far as the author is aware. The ready way in which the magnitude, and even the sign, of the charge can vary with apparently trivial changes in circumstances suggests that such a substance, even if effective one day, would not be so the next. Metals, whether earthed or not, are particularly active in imparting charge to textiles.

Interference with processing

Trouble due to static electricity occurs in many forms, which may be classified as follows.

(1) Repulsion between like charges. A bundle of yarns charged alike bows out sideways, which makes it difficult to control the positions of the threads during processing.

(2) Attraction between a charged body and a conductor. Textiles stick to various parts of the machinery.

(3) Attraction of dirt to the charged textile. Many of the small particles suspended in the atmosphere are charged, and stick firmly to a textile oppositely charged. This is known as "fog-marking."

(4) Ignition of inflammable vapours. This is a common occurrence in certain industries where organic solvents are used, but in the textile industry is confined to such processes as "doping" where cloth is coated with rubber or other materials not soluble in water. Fires in purely textile mills have been attributed to static, but, in the authors' opinion, this is doubtful.

(5) Shocks to operatives. Serious shocks only occur where some large conductor is highly insulated and charged up by the textile. They may be avoided by earthing the conductor. Small shocks may be received by induction, but are seldom worth bothering about.

(6) Increase of friction. The electrostatic attraction between opposite charges at the site of separation must increase the normal pressure between the two surfaces and lead to an increase in the frictional force. It is difficult to ascertain, in a particular case, what proportion of the observed friction is due to this effect. If the surface charge density were limited to that which can obtain in free air (about 8 e.s.u./cm^2) the extra normal pressure would not exceed 0·8 g wt/cm^2, but it seems likely that the charge density may exceed the above values before the surfaces have separated to a distance comparable with the free paths of ions in air.

Items 1, 2 and 3 are the most serious in the textile industry. The mechanical effects may require a particular stage in the processing to be slowed down to half rate, or even stopped altogether, thus interfering with production, whilst the collection of dirt reduces the market value of the products.

Dissipation

No completely successful method of preventing the separation of charge that causes static is known to the author. For this reason no attempt has been made at the Shirley Institute to prevent the occurrence of static; instead we try to dissipate it before it has had time to become a nuisance. The static may be made to leak away either through the textile itself or through the air.* The use of a dressing which makes the textile conducting might seem to be the simplest method, and it has in fact been used successfully for a number of applications, but to produce a dressing which is satisfactory in every way has proved surprisingly difficult. Raising the humidity of the air is sometimes sufficient, but is not always practical. The most generally successful way of dissipating static has been to ionize the air, either by means of a silent discharge from points, or by means of a radioactive substance. The electric method is applicable to most cases where a fire risk would not be introduced thereby, and can provide almost unlimited current. The radioactive method is only suitable for those applications where a comparatively slow rate of discharge is sufficient, at least in the textile industry. Table 1 is intended to illustrate the wide range of total currents required to prevent static trouble in three textile processes, and the even wider range in the rate at which the neutralization must be completed at any one spot on the material.

Table 1. *Factors affecting the required rate of dissipation of static in three textile processes*

	Total current needed	*Rate of motion*	*Time available*
Weaving	0·003 μA	zero	10 min
Carding	0·07 μA	1 ft/sec	0·1 sec
Warping	5·0 μA	5 ft/sec	0·01 sec

[*Weaving* is the production of cloth from two sets of yarns—the warp and weft. The effect of static is to attract dirt from the air on to the stationary warp during the night.

Carding is a process in which cotton, or other short fibres, are fluffed out, freed from the last foreign matter, and brought together to form a loose rope ("sliver"), subsequently to be drawn out and twisted into yarn. The static trouble is due to the fibres sticking to all parts of the machine.

Warping—of the sort referred to here—is a process in which several hundred yarns from separate bobbins are brought together by sections into a parallel sheet and wound on to a "beam" (like a gigantic photographic film spool) to form the warp for weaving cloth. The static trouble results from mutual repulsion of the yarns, causing them to bow out at the edges

* This is not quite an accurate description. Ions do not pass from the textile to the air, but opposite ions come from the air to neutralize those on the textile.

of each section, thus spoiling the winding and leading to breakages at a later stage.]

THE TIME FACTOR

It will be gathered from the above that the time factor is all-important in dealing with static in industry. In fact it may enter in four different ways, as follows.

(1) *Rates of static production and leakage.*[1,2] The rate of leakage to earth of the static on a textile material passing through a machine may be balanced against the rate of production of static at some point of contact with the machine, and the rate of motion of the textile. The higher the conductivity of the textile, or the slower its motion, the greater is the opportunity for static to leak away to the nearest point of contact with the machine, and the less static is left on the textile. By far the most potent factor, apart from the nature of the textile, which affects its conductivity is the moisture content, which in its turn is controlled at equilibrium by the relative humidity, and to a less extent the temperature, of the air. Several experimenters[3,4] have shown how the electrical conductivity of a textile material may rise a million-fold as the relative humidity increases from 10% to 90%. Hence it happens that the major factor determining whether static trouble will be experienced with a given material and process is the relative humidity, but that the humidity below which trouble may be expected depends upon the speed of the process.

(2) *Rates of leakage and nuisance.* In a few cases the trouble caused by the static results from a slow process such as the attraction of dirt or dust from the air ("fog-marking"). This seldom becomes visible until it has been going on for ten minutes or so; more usually it takes an hour to show itself. Hence fog-marking will cease to trouble if the static can leak away in a few minutes, but such a slow leak would have no effect at all on most of the mechanical troubles due to static, in which the textile may only take a fraction of a second to fly to some part of the machine and adhere to it. Thus it happens that with acetate rayon warping troubles occur during the whole year, whilst fog-marking is only serious in winter, when the low relative humidity in the warm mill, resulting from the low temperature outside, enables a charge to remain on the warp for hours.

(3) *Rates of static production and elimination.* When an ionizing agent is used to dissipate static by rendering the air conductive to electricity, its measure of success may be determined by the relative rates of production of static and ions. An electric static eliminator of the usual type in which a high potential is applied to a row of points is not likely to fail in this respect, however, for the current available is virtually limitless. In practice a high resistance or small capacity is placed in series with the points to avoid shock to anyone touching them, and to prevent a dangerous dissipation of energy if a short-circuit occurs. However, the limit to the current need not be set lower than 1 mA per electrode on these grounds, and this is more than ample for any textile application known to the author. It is claimed for certain American static eliminators, e.g. TAKK Static Eliminator, of this type that they are safe in the presence of inflammable vapours by reason of the small value of the coupling capacitance in series with each point. This would imply a much lower limiting current, and it is possible that some sacrifice of neutralizing ability has to be made to achieve safety.

The situation is quite different with radioactive static eliminators. Here the activity usable is limited by considerations of safety, with the result that radioactive eliminators are not usually suitable for the fastest applications. The highest currents can be obtained from α-emitters, which in practice means radium or polonium. The latter, though much safer on account of the absence of γ-rays, is prohibitively expensive and short-lived for any but very special applications. Static eliminators containing radium are much used in America, but have to be sited with care. It so happens that in the textile industry the static has usually to be discharged not far from where an operative has to stand; under these conditions it is doubtful if higher discharge currents than 1 μA could be safely obtained, for massive screening is not often practicable. Thus, referring to Table 1 above, we see that radioactive static eliminators employing radium are not fast enough for the warping application, but would be quite suitable for use in the carding of, for example, acetate staple fibre. Eliminators containing β-emitters can only, with safety, provide much smaller currents of the order of thousandths of a microampere, or under favourable circumstances a few hundredths. Their radiations are easily screened, however, since pure β-emitters, which do not emit γ-rays, are available in quantity. The ions they produce are scattered through a considerable volume of air, and β-emitters are particularly suitable where a slow neutralization of static over a wide area is required. They are well adapted for use in the first application mentioned in the table—the avoidance of "fog-marking" during weaving—and are now coming into use for this purpose.

An instructive calculation can be made which depends upon the fact that neutralization of static, and the physiological effects, are both measured by the rate of production of ions. If we take the figures given above for the weaving application as representing the least stringent case we see that the total current required will not be less than 0·003 μA, or 9 e.s.u. of current. The accepted upper limit for the rate of ionization in air where the human body may be frequently exposed to the rays is 12·5 mr/h, which, by definition, corresponds to production of ionic charge at the rate of $3{\cdot}5 \times 10^{-6}$ e.s.u. of current/cm^3. Even if the utilization of ions is 100%, a volume of 2·6 m^3 would have to be irradiated at this rate to produce the desired current. This means in practice, that whatever rays are used, a considerable space will have to be irradiated at a rate much above the "tolerance level." This space must be arranged so that no part of the human body remains in it for more than a small fraction, if any, of the working time.

(4) *Rates of utilization and recombination of ions.* When a static eliminator is employed to ionize the air in the neighbourhood of a charged textile, the positive and negative ions will be recombining all the time, and the efficiency of utilization of the ions (i.e. the percentage of ions of one sign which go to neutralize the static) will depend upon the effectiveness of the field due to the static in pulling in the ions before they are neutralized by opposite ions.

The mobility of freshly formed ions[5] of either sign in ordinary air (containing some water vapour) is of the order of 1 or 2 cm/sec per V/cm. The field near the surface of a textile material carrying 1 e.s.u. of charge per cm^2 (quite a mild case of static) is 2π e.s.u. or 1870 V/cm. Ions will thus move towards the surface with a velocity of, say, 20 m/sec, and an ion starting 20 cm away will take 0·01 sec to get there.

If it were permissible to use the published value[6] for the recombination coefficient for ions in air of $1{\cdot}6 \times 10^{-6}$ cm^3/sec* it would be possible to get a rough idea of the chance that a given ion would recombine in 0·01 sec. On this assumption we should find that an ionization rate of 12·5 mr/h would

* Sayers[7] has since given larger values up to $6{\cdot}3 \times 10^{-6}$ cm^3/sec, but even his highest value would not affect the argument.

produce (in the absence of a field drawing the ions away) an ion concentration of $6{\cdot}7 \times 10^4$ ion pairs/cm^3, and that on cessation of the ionization this would fall to half value in about 9 sec. If this were true, one would expect that there would be little chance of a particular ion failing to reach its destination, and that the efficiency would be nearly 100%, even with quite low fields. A hundred-fold increase in the ionization rate would only reduce the half value time to 0·9 sec. Experiment shows, however, that high efficiencies are not so easily reached (cf. the data in Figs. 1 and 2) and it

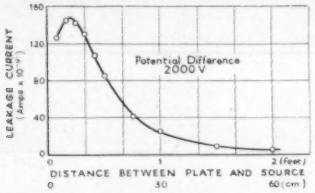

Fig. 1. Leakage current to earth from a metal plate 44 × 33 cm, held at a high potential, at various distances from an α-source (220 g of radium)

is easy to see why this should be so. The above value for the recombination coefficient was determined using X-rays as the ionizing agent. The ions were thus fairly uniformly distributed. With β-rays, and still more with α-rays, the ions are clustered round the individual paths, and their effective concentration is much greater than their average concentration, leading to quicker recombination.

The author has made no serious attempt to calculate or measure the total number of ions produced by a radioactive static eliminator, and to deduce the actual value of the efficiency in any particular application. The total number of ions produced is not, in his opinion, a very good guide to suitability of a radioactive unit for a particular task; the number of disturbing factors is such that a trial under working conditions is the only safe guide, at least until more experience has been gained. A semi-quantitative examination of the theory has, however, proved extremely useful in providing a guide to the most effective way of using a particular unit.

Experimental curves for the leakage currents from a metal plate maintained at a high positive potential with respect to earth, at various distances from two radioactive sources are shown in Figs. 1 and 2. The size of the metal plate was

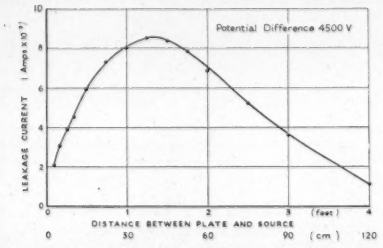

Fig. 2. Leakage current to earth from the same metal plate as in Fig. 1, at various distances from a β-source (2 mc of thallium^{204})

44 × 33 cm, the radium source was distributed over a plate 7·5 cm square, and the thallium source was disk-shaped and approximately 3·5 cm diameter. It will be seen that for each type of source there is an optimum distance; if the source is too close to the plate, some of the α- or β-particles are stopped before they have produced their full number of ions; if the source is too far away, ions have a greater chance of recombining before they can reach the plate. Experiments with different voltages on the plate showed, in fact, that under the conditions stated on the figures, saturation had been reached at all distances up to the optimum, but that beyond this point an increase in voltage caused a rise in current.

If circumstances make it necessary to site a β-ray static eliminator closer to the charged material than the optimum distance, it may be best to turn it sideways, or even to face it away from the material. This is shown in Table 2, which gives figures for the current with the same β-source and plate as mentioned before, with the source at 7·5 cm from the plate, and 3000 V on the latter.

Table 2. *Ion current to metal plate for different orientations of a β-source close to it*

Orientation	*Current (A)*
Unit facing towards plate	$4{\cdot}1 \times 10^{-9}$
Unit facing at right angles to plate	$7{\cdot}1 \times 10^{-9}$
Unit facing away from plate	$6{\cdot}9 \times 10^{-9}$

The angular distribution of β-particles in front of the source used in these experiments has been found to follow closely the cosine law as used for optical radiation from a surface. Virtually no β-rays are emitted behind the plane of the source. The essential point to remember in siting a radioactive static eliminator is that as many as possible of the ions formed should be situated where the field from the static is intense. It is not necessary that the rays from the eliminator should strike the charged material; it may, however, be convenient for them to do so. The field from the static is often limited more by the screening action of parts of the machinery than by distance. If the charged material is much surrounded by earthed conductors, it may be necessary to site a β-ray static eliminator closer than would otherwise have been desirable, in order to get the high concentration of ions near the source into a position which is not electrostatically screened from the static.

An extreme, though not obvious, form of screening occurs where a charged yarn or fabric is lying in contact with, or close to, a roller or other conducting surface. Here, although the upper surface of the textile may be freely exposed, the induced opposite charge on the earthed metal prevents the charge on the textile from producing a field on its free side. Hence there is no inducement for ions in the air to travel to the textile, and static in this position is practically unneutralizable by any form of static eliminator. Adhesion of yarns to rollers from this cause has usually to be countered by other methods, such as a higher relative humidity or the use of a conducting dressing on yarn or roller.

We may note here that the current available from a radioactive unit is proportional to the activity of the source, and independent of the amount of static, as long as the conditions are such as to favour efficient collection of the ions. Under less favourable circumstances there will not be proportionality, and in the extreme case where the number of ions used was small compared with the number recombining, the current would be proportional to the square root of the source activity and to the charge on the textile. (The concentration

of ions would vary as the square root of the activity, and the conductivity of the air would vary as the ion concentration.)

FORMS OF STATIC ELIMINATOR

By the words "static eliminator" is here meant a device which ionizes the air and thus enables the static to leak away to earth after it has been formed. The use of either a high humidity, or dressings for the textile or machinery, or special materials for rollers, guides, etc., will not be discussed here. Though all of these have been useful in particular cases, they have not yet proved of such general applicability as ionizing static eliminators. Of available ionizing means, the only two which have come into use as yet are the silent electric discharge and radioactive materials. Flames are effective ionizers, but are not welcome in a mill; ultra-violet lamps, though often suggested, are too weak in ionizing power to be useful.

Electric means of actually preventing the formation of static, as suggested by Gill and Alfrey,[8] appear promising for the future, but the author has not heard of an industrial application of this method yet.

Electric static eliminators. The simplest form of electric static eliminator consists of an earthed conductor provided with sharp points or edges placed as near as possible to, but *not* touching, the charged material. The field due to the static, concentrated in the neighbourhood of the sharp edges, produces a silent discharge which provides the necessary ions. For machines through which cloth passes continuously a *fine* earthed wire stretched parallel to the cloth surface across the width of the piece has been used with success. Since the method depends upon the presence of a strong static charge for its action, it can only reduce the charge to a certain point, and not completely eliminate it.

Static eliminators, e.g. TAKK Static Eliminator, and others by Chapman Electric Neutralizer Co. and Simco Co. have long been in use in America, and to a less extent in this country, which comprise a row of points capacitatively coupled to a highly insulated busbar to which is applied by means of a transformer an alternating potential of mains frequency with a voltage between 8000 and 12 000 V. The capacitative coupling ensures that dangerous currents cannot flow if the points are touched or if a short-circuit occurs, but enables sufficient current to pass to ionize the air. It is claimed for one make of these eliminators, TAKK Static Eliminator, that the capacity coupling each point to the busbar is so small that if sparks be drawn from the electrode the energy in each individual discharge (occurring 100 times per second in this country) is insufficient to ignite mixtures of inflammable vapours and air. The author has not had the opportunity of testing this claim. The sparks in question are very noticeable.

In this country the form of eliminator described above has been virtually superseded by a similar type (the "Shirley" Electric Static Eliminator designed by I. G. McDonald and J. B. Todd), in which two rows of points are normally used, and *rectified* potentials of 12 000 V, positive and negative respectively, are applied to the two rows. A typical electrode assembly is shown in Fig. 3, where C_1 and C_2 are the rows of points, and S is a sheet of perspex between them to prevent direct discharge from one to the other. This form of eliminator has two advantages over the alternating discharge type. The first is that the range of action is increased, since the streams of ions of opposite sign coming from the two electrodes do not recombine so quickly as the alternating bands of ions produced by the American eliminators. The second advantage is that a central power unit can be safely used to supply several score of electrode systems, the high tension being distributed by cables running in conduit round the room. If an attempt is made to do this with alternating high tension, the capacity between the cable and conduit (the latter being obligatory in this country) draws such a large

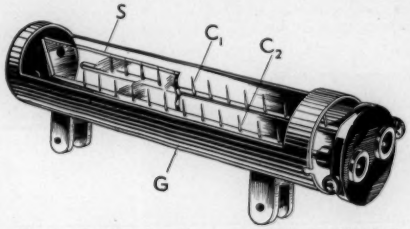

Fig. 3. Double electrode as used with the "Shirley" Electric Static Eliminator. The parts are drawn slightly separated for clarity

wattless current that the power unit has to be of low impedance, capable of providing a dangerous current in case of damage to the installation. With the rectifying system a safety resistance or cut-out can be incorporated *in the power unit* to prevent the total current exceeding a milliampere or two.

If an extra long range of action is required, the rectifying system can be used with a single electrode emitting a stream of ions of one sign only. Under these circumstances ions are not lost by recombination, though they may be lost to neighbouring earthed conductors. This method is not used unless necessary, for two reasons: firstly, the sign of the static is not always constant, and secondly, it is possible to charge up the textile by means of the eliminator if only one sign of ion is used with too high a voltage on the electrode, especially if the textile is backed by an earthed body.

Radioactive static eliminator: α-ray. These normally contain radium and its daughter products incorporated in silver and gold foil, carried and protected by stout channel-section metal. So far as the author is aware, they are only commercially available from abroad [Ionotron from Eldorado Mining and Refining (1944) Ltd.], but a similar radium-bearing foil is produced in this country by Radiochemical Centre, Amersham, Bucks, from which physicists can make their own appliances. α-ray static eliminators are intermediate in speed between electric and β-ray eliminators, and are sufficiently rapid for the application to carding mentioned in Table 1, but they could not safely be used in a sufficiently strong form to assist in the warping of acetate rayon. They have the advantages over electric eliminators of simplicity and complete absence of fire risk in the presence of inflammable vapours. They have, however, the disadvantages of risk from the γ-rays, which makes their installation near to the operating positions of machines inadvisable, and also of cost, where more than one or two are needed. The cost of radioactive static eliminators is proportional to the number of points where elimination is required, but this is not true of electric eliminators.

α-ray static eliminators which do not emit γ-rays can be made with the aid of polonium, and are available commercially in America [Alphatron, Eldorado Mining and Refining (1944) Ltd.]. Their cost and short "half-life" renders their use uneconomic except in very special cases.

The use of radium sources too small to be dangerous has possibilities where a highly localized action of moderate rapidity is required, but has not yet occurred in the textile industry to any great extent.

Radioactive static eliminators: β-ray. These are only suitable where a slow rate of action is sufficient. In such cases they have the advantages of simplicity and low initial cost. Their risks to personnel are much less than those of eliminators using radium, for emitters of pure β-rays are easily available, and β-rays are readily screened, and have a low penetrating power into the tissues, thus affecting only the few millimetres near the surface.

The isotope at present most used for this purpose is thallium^{204}, which is obtained by the action of neutrons on normal thallium^{203} placed in the pile, and has a "half-life" of 2·7 years, emitting β-rays (only) of maximum energy 0·775 MeV. It may be obtained incorporated in silver foil in this country from Radiochemical Centre, Amersham, Bucks. The foil is most suitable for sources of moderate activity, as it cannot be made with more than a certain activity per unit area. For sources stronger than a millicurie or so, or where the source has to be concentrated into a small area, a method of construction is commonly used[9] in which active thallous nitrate is melted on a brass plate and heated till it decomposes into oxide and a little metal, when it is found to adhere strongly, if in a thin layer. The whole is then sealed up behind a thin foil of aluminium and Pliofilm, and guarded with a stout wire mesh. Small circular units of this type, "Shirley" Radioactive Static Eliminator, containing 2 mc of thallium^{204} are now coming into large scale use on looms weaving acetate rayon or nylon warps, for the avoidance of "fog-marking."

Fig. 4 shows a cross-section of one of these units. *A* is a dished brass disk carrying the active thallium coating on its under side. Immediately in front of this is a thin sheet *B* of aluminium foil coated on both sides with Pliofilm (rubber hydrochloride). Separated from this by a washer is a stout dished wire gauze cover *C*, which is strong enough to resist any likely thumb pressure, and whose mesh is so arranged that an ordinary pencil point cannot reach the foil to damage it. The assembly is firmly held in a plated brass cover *D* whose rim is turned in so that the unit cannot be opened except with a hacksaw. *E* is a brass cup, fastened to some part of the loom, in which the radioactive unit rests during the day (it is only needed at night). When the loom is stopped in the evening the unit is lifted out of its cup and allowed to hang down over the warp by the chain *F*. The stalk *G* serves as a handle on the safe side of the unit, and also ensures that the latter hangs in the right position facing downwards.

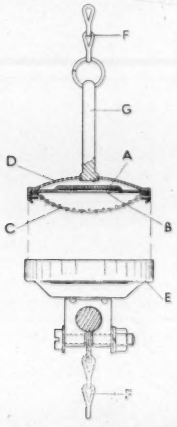

Fig. 4. Cross-section of the "Shirley" Radioactive Static Eliminator, containing 2 mc of thallium^{204}

Considerable attention has been given to the question of safety, the cup and cover being thick enough to stop all β-rays. The weaver is encouraged to keep the unit in its cup during the day by the fact that it would be very inconvenient in the hanging position. However, even if it was left hanging for several days in succession, it is considered unlikely that any harm would result, for the weaver's hands would not be sufficiently close for a long enough time for a dangerous dose to result. Fig. 5 shows the measured ionization rate at various distances along the axis. H.M. Medical Inspectors of Factories have been kept fully informed throughout this work. The units have proved completely successful in preventing "fog-marking" on acetate rayon and nylon warps.

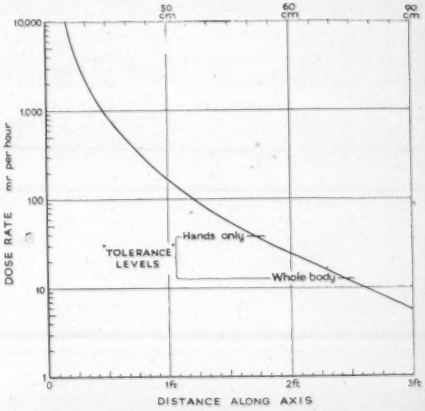

Fig. 5. Ionization rate at various distances along the axis of a "Shirley" Radioactive Static Eliminator

It is hoped that it will eventually be possible to use strontium^{90} in place of thallium. This isotope, together with its daughter product yttrium,^{90} has a "half-life" of 22 years, and emits β-rays of maximum energy 2·2 MeV having a much longer range than those from thallium^{204}. Strontium^{90} is formed by fission of uranium in the pile, and should eventually be available in quantity.

ACKNOWLEDGEMENTS

I wish to thank the Director and Council of the British Cotton Industry Research Association for permission to publish this work, and Mr. H. R. Fraser for carrying out some of the measurements.

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DISCUSSION

Mr. R. F. Ellis: I recently made a brief investigation into the behaviour of the static charge generated during weaving on warps of cellulose acetate rayon, and I would like to mention one feature of the results which seems of interest in connexion with fog-marking.

It was found that the manner in which a warp charged up while the loom was running, and discharged after the loom stopped, could be described reasonably well by the usual equations for a resistance-capacity system. Rates of charging and discharging varied from loom to loom, but in no case was a time constant for discharge found to be greater than 60 min. This rate of discharge is slow enough to account for fog-marking, yet it conflicts in its implications with the view, commonly held in textile mills, that fog-marking more frequently occurs during a week-end stop than during an overnight stop.

These two observations can be reconciled if we assume that the highly-charged yarn found just after the loom stops collects dust less efficiently than it does some hours later when its charge is much diminished. The explanation of this is possibly connected with a point that arose from Lucas and Lowe's paper on electrostatic precipitation (see p. S 40), i.e. the capture of a charged particle by an electrode, and its subsequent rejection following upon transfer of charge from electrode to particle. It seems possible that this process takes place on yarns at high charge densities, and that the yarn starts to collect dirt only when the charge density is much reduced.

Mr. N. W. Alford: My firm found that static electrification of our cellulose acetate materials can be reduced to negligible proportions by light contact with cotton fabric. Any initial charge seems to be neutralized by this action. The results obtained by this simple technique are often much more satisfactory than those obtained by means of a static eliminator. When the temperature is about 90° C the cotton is treated with an anti-static agent such as sulphonated oil. This technique does not work with Bakelite or polystyrene films.

Author's reply: Mr. Ellis's suggestion is most interesting. I should like to know whether his experiments were done at the low relative humidities common in mills during the dry frosty weather which is most conducive to fog-marking. I am not clear why the charging of a particle on contact with the warp, and its subsequent repulsion, should take place when the warp is highly charged, but not with a small charge on the warp. Perhaps something like a "flash-over" on the surface of the particle should account for this. It is certainly a question which should be followed up.

Static electricity on rubber-tyred vehicles

By D. BULGIN, A.I.R.I., A.Inst.P., Dunlop Research Centre, Dunlop Rubber Co., Ltd., Birmingham

The electrostatic charge which originates at the separation of the tyre tread from the road raises the potential of road vehicles to a maximum of 100 000 V, the value depending on roughness of the road surface, vehicle speed and tyre tread resistance. The inter-connexion of these factors is given in the paper with both experimental and theoretically derived values of voltage. Harmful effects include shock from the vehicle, radio interference (small) and puncture of the inner tube due to ozone originating between the tube and the inner wall of the tyre. Elimination of these effects is obtained using tyres of electrical resistance of less than $10^9\ \Omega$.

A tyre made from a rubber compound of high electrical resistance, when rolling on a dry road, is an excellent generator of electrostatic charges owing to the intimate contact between the tyre tread and the road surface, caused by the high contact pressure. On smooth dry roads a vehicle moving at a normal speed on tyres which have a tread resistivity 10^{10}–$10^{13}\ \Omega$ cm, will be charged to a negative potential of 15 000 to 50 000 V to earth, while values of 100 000 V are not uncommon. Even the rider of a pedal cycle will acquire a potential of some 5000 V to earth. Under conditions where the road surface becomes an exceptionally good insulator—for example, an asphalt surface in very dry weather—the road surface itself retains the positive charges and surface potentials of 30 000 V have been measured.

A typical voltage-distance graph obtained by taking readings with a Baldwin–Dunlop Statigun[1] from the platform of a bus on various road surfaces is given in Fig. 1. The stable voltage level is reached after travelling about 50 ft from rest.

METHOD OF STATIC GENERATION BY TYRES

As the tyre tread continually makes and breaks contact with the road, a static charge is generated which is carried around on the tread as the wheel revolves. The capacity of the condenser formed by an element of the tread and the road surface rapidly decreases as the element passes away from the contact point and consequently the charge rises in voltage. Voltage gradients are thereby set up between the tread element and the contact point and also across the side of the tyre to the rim of the wheel. The vehicle itself becomes charged to a steady potential which will be determined by the relative resistance of the various leakage paths and by

the voltage to which the charge is raised. Induction effects can also be present.

The voltage distribution on the tread of a tyre running on an earthed steel drum, as measured with the Statigun, is given in Fig. 2(*a*) and across the sidewall in Fig. 2(*b*). Observed values from experimental tyres of different specific

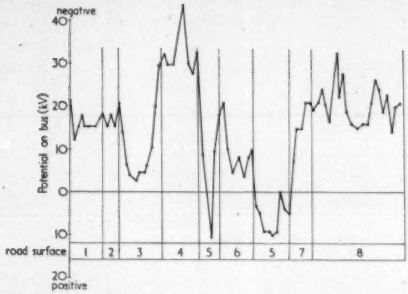

Fig. 1. Voltage-distance graph obtained when bus travelling on various road surfaces

1. Smooth tar.
2. Wood.
3. Rough tar on asphalt.
4. Smooth asphalt.
5. Tar on wood.
6. Asphalt on wood.
7. Tarmac.
8. Stone sets.

resistance are given in Fig. 3. It will be seen that the voltage at first rises, owing to capacity decrease. The lower the tyre resistance, the smaller the magnitude of the voltage lobe. The voltage leaking on to the rim is negligible at tyre electrical resistances below $10^8\ \Omega$ (at 30 m.p.h.).

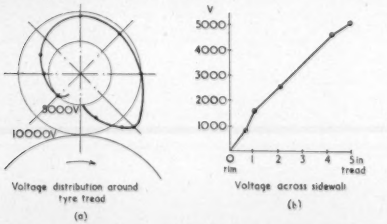

Fig. 2. Voltage distribution on a tyre running on an earthed steel drum

EFFECT OF ROAD SPEED AND TYRE ELECTRICAL RESISTANCE ON THE VEHICLE VOLTAGE

In another contribution in this supplement,[2] a formula is derived which permits the calculation of the effect of rate of generation of charge on the voltage attained, under specified leakage resistance conditions.

$$V = \frac{Asq}{1 + Acs}$$

where V = steady state voltage (volts)
A = area of surface separated per second (cm^2)
q = charge density (C/cm^2)
c = capacity of charged surface (F/cm^2)
s = leakage resistance (Ω).

If the charge density is assessed as approximately 20% of the theoretical limit (owing to imperfections of surface contact) and appropriate dimensions for the tyres are used, the relationship between vehicle voltage and tyre electrical

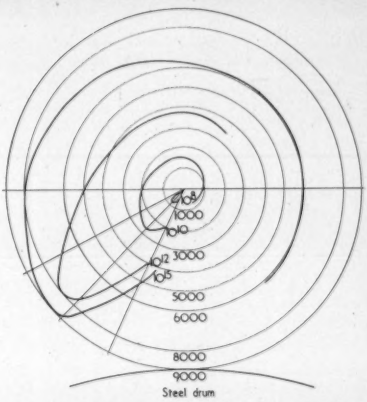

Fig. 3. Distribution of voltage (V) observed with tyres of various specific resistances (10^8–$10^{15}\ \Omega$ cm)

resistance at a speed of 40–50 m.p.h. both as calculated and obtained by experiment are shown in Fig. 4. The agreement between the calculated and experimental values is reasonably good, in view of the difficulty of knowing the effective values of leakage resistance within the tyres along the path to the contact point with the road.

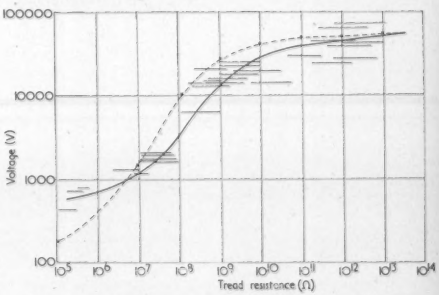

Fig. 4. Voltage on vehicle-tread resistance relationship at a speed of 40–50 m.p.h.

——— Voltage on cars at 40–50 m.p.h.
– – – – Calculated values.
——— Range of resistances of various sets of tyres.

The effect of vehicle speed on voltage, when tyres of various resistance are used, is shown in Fig. 5; again the computed and measured voltages show good agreement. It is of interest to note that with tyres of low electrical resistance the voltage is proportional to speed, but at high resistance figures the voltage tends towards a limiting value.

EFFECT OF ROUGHNESS OF ROAD SURFACE

The effect of the degree of road roughness is to alter the area of the tread pattern in intimate contact with the road. Determinations of this area have been made by inking the road surface and rolling the vehicle over a sheet of paper placed on the inked area. By photometric methods the amount of ink pick-up has been used to assess relative

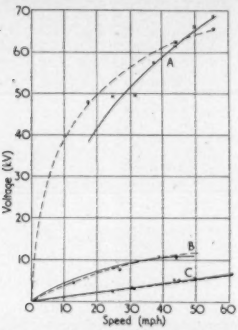

Fig. 5. Voltage on vehicle-speed relationship when tyres of various resistances are used

	A	*B*	*C*
× Observed values	10^{10}–10^{12}	10^{9}–10^{10}	$5 \times 10^{8}\ \Omega$
○ Computed values	5×10^{10}	$1{\cdot}25 \times 10^{9}$	$5 \times 10^{8}\ \Omega$

smoothness of the surface, so that this value could be compared with the voltage generated on a vehicle passing over this particular stretch.

The results are given in Fig. 6, and show that the voltage is approximately proportional to the road smoothness. It confirms the expected relationship since the maximum voltage to which the charge can be raised under the existent capacity conditions is about 100 kV.

It is of interest in this connexion to observe that the static charges on cars of post-war design have a voltage about 30% greater than those of pre-war design. This is due to the fact that the modern car has a much greater tyre-mudguard clearance to accommodate its softer springing and consequently the capacity of the tread of the tyre to the vehicle is reduced.

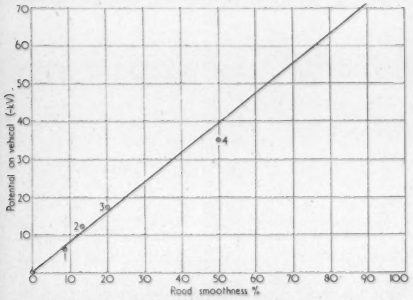

Fig. 6. Effect of road smoothness on voltage generated at 30 m.p.h. The theoretical maximum voltage at 100% smoothness is 100 kV

1. Rough tarmac.
2. Rough surface asphalt.
3. Smooth tarmac.
4. Smooth asphalt.

OPERATIONAL EFFECTS OF STATIC CHARGES ON VEHICLES IN SERVICE

Operational effects of static charges on vehicles are threefold: electrical shock to the human body, radio interference and a certain tube defect known as "ozone puncture."

The electrical shock arises from the stored energy in the capacitor formed by the vehicle and earth. As the vehicle has a capacity of about 600 pF, the stored energy at 60 000 V is about 1 j. This can give a shock comparable to that from a sparking plug and may lead to an accident from muscular reaction if the shock occurs when a person is mounting a bus. The shock would only be experienced on touching the vehicle and not on dismounting from it, since only in the former case does the spark pass to the fingers.

Tests with observers in the laboratory, when touching capacitors of 740 and 4100 pF, charged to voltage up to 25 000 V (the maximum available) gave rise to the following physical reactions:

Voltage on the condenser kV	*Energy in 740 pF condenser in mj*	*Reaction when touched by hand*	*Energy in 4100 pF condenser in mj*	*Reaction when touched by hand*
1	0·4	Not detectable	—	—
2	1·5	Detectable	8·2	Prick
5	9·3	Prick	51	Sharp prick
10	37	Sharp prick	205	Slight jerk
15	83	Slight jerk	460	Jerk
20	149	Slight jerk	820	Sharp jerk
25	232	Moderate jerk	—	—

It will be seen that the reaction depends primarily on the energy and not on the voltage of the charge. It was deduced that voltages of less than 10 000 V would not give rise to noticeable effects under the circumstances existing at the moment of boarding a bus or touching a vehicle, but that higher voltages could give rise to shocks.

For several years past the majority of passenger carrying vehicles have been fitted with "non-static" tyres, having a resistance when new of 100 000 Ω to 5 MΩ and less than 10^{9} Ω at any time in their life (the resistance of the conductive rubber increases as the tyre wears). An extensive investigation showed that the static voltage on vehicles with "non-static" tyres averaged 11 kV, observed when the vehicles were in motion at usual speeds and to a lower figure when contacted by passengers. This compares with an average of 39 kV on comparable vehicles on normal tyres having the higher electrical resistance of 10^{11}–10^{14} Ω.

It would be technically feasible to reduce the voltage to a considerably lower level by using tyres of still lower electrical resistance, but this step is not necessary in relation to normal operating conditions with road vehicles. It would, moreover, result in tyres having such a low electrical resistance as to involve severe electrical shocks and possibly fire risk arising from contact with 230 V mains supply.

"Non-static" tyres with a resistance of less than 10^{9} Ω have another advantage. The reduced electrical resistance of the tyre sidewall increases the leakage rate of the vehicle to earth if the road surface is of a comparable low resistance, so that some protection against residual charges on the vehicle is obtained. This is of importance when refuelling or in loading up vehicles carrying inflammable liquids.

Owing, however, to the uncontrollable nature of the road resistance, which may vary between zero under wet conditions and $10^{16}\ \Omega$ when very dry, the use of conductive tyres cannot permit dispensing with the customary direct bonding and earthing of vehicles when handling inflammable liquids. This is particularly the case in the refuelling of aircraft.

RADIO INTERFERENCE

At first sight it would perhaps be anticipated that the continued generation and leakage of tyre generated static charge from a vehicle charged to approximately 50 000 V would result in a considerable noise level in radio receivers on the vehicle. This, however, is not the case and in practice static voltage has a negligible effect on radio reception of normal strength broadcast signals. The effect can nevertheless be disturbing when receiving weak signals, such as from distant broadcast stations, or with mobile communication equipment. Reduction of the static voltage in these situations can reduce the background by 6 db or more and make otherwise difficult reception intelligible.

OZONE PUNCTURES

The photograph in Fig. 7 shows a peculiar type of tube failure known as "ozone puncture" or in the U.S.A. as "sparkbite." It has the characteristics of a slow puncture leading to tyre deflation, but no physical puncturing agent can be found. However, perforations are found in the tube, usually on the sides and less frequently on the crown of the tube.

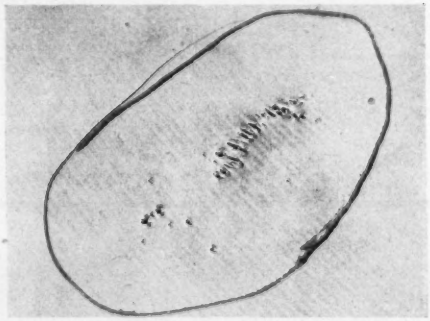

Fig. 7. Typical tube failure known as "ozone puncture" or "sparkbite"

These arise from the generation of ozone at points between the tube and the inside of the tyre. (Ozone very rapidly attacks rubber in a characteristic way causing a slit normal to the principal stress.)

This phenomenon arises from the large potential gradient set up across the inside surface of the tyre from the rim to the portion in contact with the ground, as the tyre rotates. Since the resistance of the inside of the tyre will not necessarily be uniform, ionization can take place if the voltage gradient locally exceeds 30 000 V/cm. This can occur at resistance irregularities in the cords or rubber, or at hair cracks in any paint layer on the inside of the tyre.

In such cases repeated ionization at the same places on the inside of the tyre generates ozone in sufficient quantity to attack the stretched rubber of the inner tube. Punctures can occur quite rapidly in severe cases. The pattern of the points at which ionization occurs is quite stable, so that the same pattern of damage to the tube can be repeated, as new tubes are put into the offending cover. The voltage gradient arises between the rim and the inside of the tyre at the point where the latter contacts the road owing to the considerable increase in capacity to earth of the inside of the tyre at this point. This effect reduces the voltage inside the tyre, which is normally at the value of that of the rim, to approximately zero and causes a surge of current across the inside of the tyre to charge the condenser. As the charged area moves away from contact with the road, its capacity decreases and its voltage may rise above that of the surrounding areas. A discharge can occur back to the rim and to the new low potential area which has arisen at the point in contact with the ground.

Fig. 8 shows the disposition of capacity and resistance in a tyre. Measured values show that

$$r = s = 5 \times 10^{10}\ \Omega \text{ at } 10 \text{ kV potential (per cm width)}$$
$$= 5 \times 10^{8}\ \Omega \text{ at } 30 \text{ kV potential (per cm width)}$$
$$C_1 = 2 \times 10^{-12}\ \text{F/cm}^2.$$

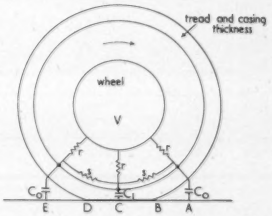

Fig. 8. Capacity and resistance distribution in a running tyre

Calculations on a typical tyre at 50 m.p.h. show that the contact time is 6/1000 sec and that in this time the voltage on the contact area will rise to approximately 50% of that on the rim. The maximum current through r will be approximately 100 μA.

As the capacity of the element decreases (as the tyre tread leaves the road), the voltage will rise rapidly, owing both to the rise in voltage of the existing charge, and the higher rate of rise of voltage due to charge leaking from the rim through r. As the voltages of the element and the rim become similar, the effective resistance of r rises and so the time constant $C_0 r$ increases.

If the rate of decrease in capacity of the condenser, due to rotation of the tyre, is greater than the time constant of the discharge paths of the condenser, its voltage will rise above that of the rim and then rapidly decrease to that of the rim, as shown in Fig. 9.

In practice the situation is complex, owing to the non-ohmic characteristics of the resistance paths, but essentially in a revolving tyre on a charged wheel there will be leakage current across the inside through r entering the contact area and a return current through r to the rim at more remote positions. There will also be a circulatory current in the crown of the tyre through s, from the area leaving the contact area back to the new contact area, as the charge is carried around in the revolving tyre.

This process is repeated as the tyre revolves, and the recurrent slight ionization at any discontinuities in the current paths results in ozone generation and damage to the rubber. It should perhaps be emphasized that this type of tyre defect is relatively rare, but it is of technical interest because it arises directly from the generation of static charges. It is prevented by removing the cause, namely the static voltage, by using a conductive rubber tread, such as is found in the "non-static" type of tyre.

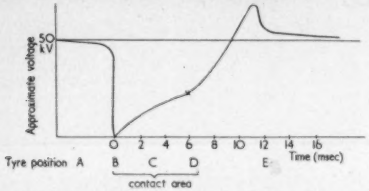

Fig. 9. Approximate voltage of running tyre. The voltage of the rim is approximately 50 kV

ACKNOWLEDGEMENT

This paper is based on work carried out at the Research Centre of the Dunlop Rubber Co., Ltd., and the author expresses his thanks to the company for permission to publish the results.

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Factors in the design of an operating theatre free from electrostatic risks

By D. BULGIN, A.I.R.I., A.Inst.P., Dunlop Research Centre, Dunlop Rubber Co., Ltd., Birmingham

A theoretical treatment is given of the factors governing the voltage attained by surfaces under stated conditions of separation and electrical resistance. The results are supported by observed values and indicate that the resistance of rubber articles (measured under conditions defined by British Standard Specifications for anti-static and conductive rubbers) should lie between 100 000 Ω and 10 MΩ.

It is considered that only "anti-static" (conductive) rubber and cotton surfaces should be permitted in operating theatres and that the relative humidity of the atmosphere should exceed 65%.

Static electricity has been a hazard in operating theatres since ether and hydrocarbon vapours replaced chloroform and non-inflammable substances as anaesthetics.

Explosions in such circumstances may have severe or fatal consequences to the anaesthetized person and also can cause burns and injury by flying glass to others present. As anaesthetics frequently are used mixed with oxygen, the explosion can be of considerable violence and the increased oxygen content also appreciably lowers the spark energy required for ignition.

Rubber and plastic materials are almost essential in operating techniques because of their non-absorbent and easily sterilized surfaces and uses include beds, seats, sheeting, aprons, wheels, shoes, gloves, and also as tubing and breathing bags on the anaesthetic apparatus. This high concentration of surfaces which are liable to produce static charges on casual movement is probably not found in any other situation. Since the vapour-oxygen mixtures can be ignited with as little energy as 1 μj, compared with a minimum of 200 μj for mixtures with air, ignition is more likely than in most industrial situations.

Recently rubber has been developed which is sufficiently conductive to readily convey static-initiated currents; materials are also available for the treatment of surfaces to make them "anti-static." Thus it is possible to design equipment which cannot produce a dangerous level of static charge under the conditions of the operating theatre.

ENERGY FOR IGNITION

It is first necessary to determine the energy in a static spark which is required to ignite an inflammable vapour-oxygen or air mixture. Recent work by Guest, Sikora and Lewis[1] gives considerable data on this. There are three principal conditions which affect the minimum energy level at which ignition occurs.

(*a*) Percentage of inflammable vapour in the mixture.
(*b*) The ratio of oxygen to oxygen plus nitrogen (or helium).
(*c*) Critical spark length (or voltage) below which a considerable increase of energy is required to effect ignition.

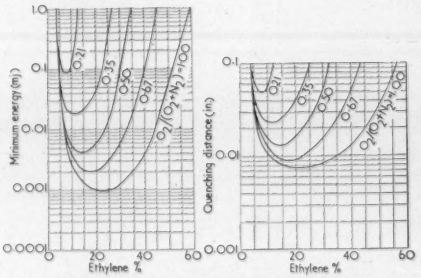

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Fig. 1. Values of minimum energy and quenching distance for ethylene

Figs. 1 to 4, reproduced from their paper, give data on these factors for mixtures of ethylene, diethyl ether and cyclopropane with various concentrations of oxygen and nitrogen, and show that all require about or rather less than 1 μj of energy to cause ignition of their most sensitive

mixtures. When the vapour is mixed with nitrous oxide and oxygen the minimum energy is raised by a factor of 10 (Fig. 3) and with air (Fig. 4) by a factor of about 200.

In order to be safe from ignition, since vapour mixtures may include the most sensitive one, the voltage must not exceed 1000 V and the energy in the spark 0·8 μj, or the energy on a 1·6 $\mu\mu$F capacitor at 1000 V. If the capacity is

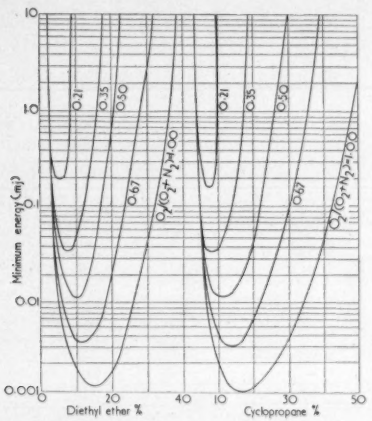

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Fig. 2. Minimum ignition energy curves for ether-oxygen and cyclopropane-oxygen mixtures, showing relative effects of dilution with nitrogen

greatly increased, ignition can be achieved at a somewhat lower voltage (650 V).[1]

It should also be noted that induction effects from electric circuits, particularly high voltage ones such as X-ray sets, sparks or arcs in electric circuits and induced static charges can also cause ignition, so that consideration must be given to these risks.

The level of hazard in different areas of the theatre varies considerably since the dilution of both the anaesthetic vapour and the oxygen with air increases the energy required (see Figs. 1 and 2). At quite small distances from the sources of the undiluted vapour-oxygen mixture, the energy required may be increased 10 to 20 times, while in reasonably remote areas the vapour is likely to be below the ignitable limits.[2]

Zone 1. The highly dangerous area, comprising the anaesthetic machine, breathing bag, tubing, face mask, patient's head, and the immediate vicinity of the anaesthetist.

Zone 2. The area requiring considerably greater energy to effect ignition. A zone extending from approximately 1 ft distance from the outer surfaces of the above items, for about 3 ft in all directions.

Zone 3. The area outside the above Zone 2, in which the vapour normally will be below the ignition limit.

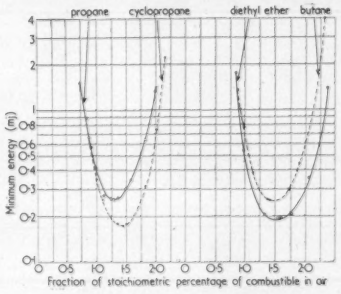

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Fig. 4. Minimum ignition energies of combustible air mixtures in relation to the stoichiometric percentage in air

It should be noted, however, that if high static voltages exist in any part of the theatre, induction of charges from one zone to the other may occur so that, apart from indicating the region of greatest risk in which the greatest precautions should be taken, zoning a theatre does not provide a solution of the problem.

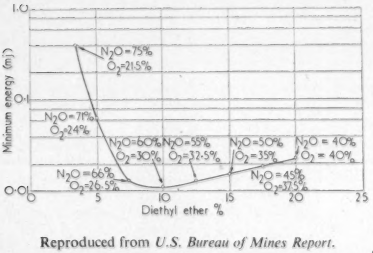

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Fig. 3. Minimum spark energies required for ignition of various mixtures of nitrous oxide, oxygen and diethyl ether

USE OF LOW RESISTANCE PATHS

If all surfaces in the theatre could be bonded together at a very low resistance, static risks could not arise, but it is not possible to make rubber and other normally insulating materials with extremely low specific resistances; 1000 to 10 000 Ω may be taken as a practical minimum for soft rubber articles, while the surface of fabrics treated with antistatic agents are rarely below 1000 MΩ per unit square.

A second and important consideration against using extremely low resistance is that electric power applied to portable lamps and tools may be used. The insulating nature of ordinary rubber footwear and of the floor provides an appreciable safeguard to personnel in the events of faults developing on unearthed apparatus. This safeguard would be removed if low resistance items were used.

A current of more than about 8 mA through the body may result in a fatality, so that a minimum circuit resistance of

the order of 100 000 Ω is required for electrical safety. This will permit a current of 2·3 MA from 230 V mains. A resistance of 100 000 Ω to earth therefore may be regarded as a minimum value of resistance for shoes and many other rubber articles in the theatre, although the use of lower values for particular items such as breathing bags and tubing need not be excluded.

ELECTROSTATIC VOLTAGES DEVELOPED ON A SYSTEM OF FINITE RESISTANCE

In considering problems involving electrification by separation of surfaces, it is necessary to know the voltage of such surfaces at any time and in particular the maximum value the voltage can attain when the charge is simultaneously

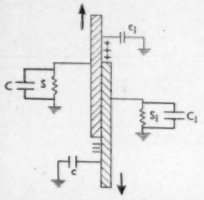


Fig. 5. Conditions arising when two surfaces are separated

leaking to earth. The conditions arising when two surfaces are separated is given in Fig. 5 and the electrical circuit in Fig. 6 gives the equivalent of one of the surfaces with its

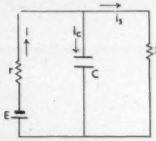


Fig. 6. Circuit equivalent of one surface

associated values of capacity and resistance. The following variables govern the level of the static voltage at any instant:

Charging source

q = the density of charge on the charging surface (C/cm²).
c = the capacity of the charging surface (F/cm²).
E = the voltage developed on the charging surface ($q = Ec$).
A = the area of charged surface discharged per second.
r = the effective resistance of the source (Ω).

Charged system

s = the shunt resistance (Ω).
C = the total capacity of the system being charged (F).
Q = the total charge on the system (C).
V = the voltage to which the system becomes charged ($Q = VC$).
t = time (sec).

It is required to know the voltage V developed across C at any time t.

The current i from the source E divides into currents:
i_c charging the condenser.
i_s passing through the resistance s. Then at any time t the voltage V across C will be Q/C.

$$E = ri + Q/C \tag{1}$$

$$V = Q/C = s \tag{2}$$

$$i_c = dQ/dt \tag{3}$$

$$i = i_c + i_s \tag{4}$$

If $Q = 0$ when $t = 0$ the solution of these equations is

$$V_t = \frac{Es}{(r+s)}\left\{1 - \exp\left[\frac{t(r+s)}{Crs}\right]\right\} \tag{5}$$

This equation is the general case for the voltage on a charged condenser system with a parallel leakage resistance, at any time t after commencement of charging.

If we now consider the charging source which is represented in the above equation by a voltage E in series with a resistance r, it will, in practice, be a surface charged to a density of q C/cm², with a capacity to earth c, and delivering its charge from an area A cm² per second to the charged body.

Since 1 C = 1 A/sec, the current from an area A per second with charge q C per cm² = i A.

Hence $$i = Aq = AcE$$

Since $$q = cE$$

$$r = E/i = 1/Ac = E/Aq$$

Hence in equation (5), substituting for r,

$$V_t = \frac{Asq}{1 + Acs}\left\{1 - \exp\left[\frac{-t(1 + Acs)}{Cs}\right]\right\} \tag{6}$$

In the general case, to obtain the value of the voltage at any time t requires knowledge of A, c, s, C, t, q, all of which are known quantities.

If the steady maximum voltage is required, i.e. the voltage when $t = \infty$ the equation reduces to

$$V = \frac{Asq}{1 + Acs} \tag{7}$$

(since $q = Ec$ other forms of the equation can be constructed), and it will be seen that the value of C the capacity of the charged system and time t no longer enters the calculation.

APPLICATION TO THE LIMITATION OF STATIC VOLTAGES

The maximum value of q the surface charge density is determined by the ionization potential of air.

A value of 30 000 V/cm gives a value for q of $2{\cdot}65 \times 10^{-9}$ C/cm² while c, the capacity of the surface per cm², is determined by its distance from other surfaces. Values of 0·1 to 10 cm can be considered likely for two surfaces being separated from each other, corresponding to capacities from $0{\cdot}088 \times 10^{-11}$ to $0{\cdot}088 \times 10^{-13}$ F/cm².

In order to provide an adequate margin of safety in the theatre the maximum instantaneous voltage should be limited to 350 V. This is substantially below the experimentally determined voltages of 650 to 1000 V mentioned earlier.

The value of the product of the rate of separation and the shunt resistance, As, can be obtained from equation (7).

In the case of 0·1 cm separation $c = 0{\cdot}088 \times 10^{-11}$ F/cm²

$$350 = \frac{As\ 2{\cdot}65 \times 10^{-9}}{1 + As\ 0{\cdot}088 \times 10^{-11}}$$

$$As = 1{\cdot}5 \times 10^{11}$$

For 1·0 cm separation $c = 0{\cdot}088 \times 10^{-12}$ F/cm²

$$As = 1{\cdot}5 \times 10^{12}$$

and for 10 cm separation $c = 0{\cdot}088 \times 10^{-13}$ F/cm²

$$As = 1{\cdot}5 \times 10^{13}$$

Likely values of rate of separation of surfaces by manual movement have an upper limit of about 10^4 cm^2/sec so that the values of s, the shunt resistance to ensure that the instantaneous voltage does not exceed 350 V, can be calculated.

Area separated cm^2/sec	*Value of s for* $C = 0{\cdot}088 \times 10^{-11}$ F/cm^2	$C = 0{\cdot}088 \times 10^{-12}$ F/cm^2	$C = 0{\cdot}088 \times 10^{-13}$ F/cm^2
100	$1{\cdot}5 \times 10^9\ \Omega$	$1{\cdot}5 \times 10^{10}\ \Omega$	$1{\cdot}5 \times 10^{11}\ \Omega$
1000	$1{\cdot}5 \times 10^8$	$1{\cdot}5 \times 10^9$	$1{\cdot}5 \times 10^{10}$
10000	$1{\cdot}5 \times 10^7$	$1{\cdot}5 \times 10^8$	$1{\cdot}5 \times 10^9$

It is therefore evident that if the insulating rubber is replaced by antistatic (conductive) rubber with a resistance of not more than 10 MΩ between any two points, and not less than 100000 Ω to earth,* the chance of a dangerous static discharge is made negligible.

It is also clear from this treatment that the rate of separation of surfaces is a factor of equal weight to that of shunt resistance, so that high rates of separation of surfaces should be avoided in the most critical zone.

EXPERIMENTAL RESULTS

Guest, Sikora and Lewis[1] (see above) have determined experimentally the rate of potential rise and the maximum potentials attained during typical manipulations in a theatre.

Extracts from their results are given below:

	Maximum voltage V
1. Person moving on and rising from an artificial leather seat on a metal chair. Chair insulated from earth	18400
2. Ditto. Chair frame earthed through 20 MΩ	170
3. Voltage acquired by the person in the above chair when wearing shoes of 50000 Ω resistance to the floor. Chair frame insulated	220
4. Ditto. Chair frame earthed to floor by 3 MΩ resistor	135
5. Voltage acquired by an insulated operating table when a cotton sheet was stripped from a rubber mattress	15800
6. Ditto. Table earthed through 20 MΩ resistor	225
7. Ditto. Table earthed through 50 MΩ resistor	450

The time taken for the voltage to reach its maximum was 0·1 to 0·3 sec when the object was earthed through a resistance and 0·3 to 0·6 sec when highly insulated.

It will be seen that these tests confirm the conclusions made from the above calculation; both the author's value of resistance limits (100000 Ω to 10 MΩ) and those arrived at by the reporters of the above experiment (100000 Ω to 1 to 2 MΩ) are in substantial agreement. Tests made in this country in 1946[3] confirm these findings.

It is of course essential that the flooring in the area should be of comparable resistance to that of the items used on it, otherwise equalization or earthing of charges could not occur. Conductive terrazzo and concrete with resistance from 0·1 to 10 MΩ and conductive rubber and plastic are available for flooring.

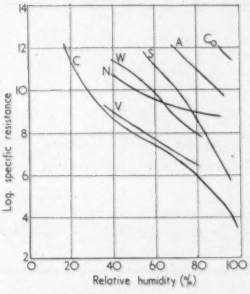
STATIC ON FABRIC AND PLASTIC SURFACES

Other potential sources of static in an operating theatre are fabrics and plastic sheeting. The general considerations which have been applied to the rubber articles are equally valid in this connexion.

Methods of increasing the conductivity of fabrics are different from that applied to rubber which can be increased in conductivity by compounding with suitable forms of colloidal carbon to give materials known as antistatic and conductive rubbers. Two main methods are used, firstly the adsorption of moisture from the surrounding atmosphere in the case of fabrics and, secondly, the treatment of the surface of the materials with antistatic agents.

ATMOSPHERIC MOISTURE

The specific resistances of textile fibres in equilibrium with the atmosphere at different humidities are given in Fig. 7 from a review of the subject by Hearle.[4] It should be noted that the logarithm of the specific resistance may vary by ± 1 with materials of different origin and will tend to decrease a little at higher temperatures. The change of resistance is of the order of 20% per 1% humidity change. Cotton and viscose rayon are, at the same relative humidity, about 100 times more conductive than nylon and wool, 1000 times more than silk and 100000 times more than acetate rayon and acetylated cotton.



Reproduced from *Journal of Textile Institute*.

Fig. 7. Logarithm of specific resistances of various textile fibres in equilibrium with the atmosphere at different humidities

C, cotton; *V*, viscose rayon; *A*, acetate rayon; *W*, wool; *S*, silk; *N*, nylon; C_0, acetylated cotton.

Since the materials are used in a sheet form, the resistance per unit square will be about 100 times greater than the specific resistance. It is clear then that only cotton and viscose rayon in *equilibrium with the atmosphere at* 65% *or higher relative humidity*, even approximate to the safe resistance criteria given above.

In view of the virtual impossibility of distinguishing between acetate and viscose rayon fabrics at sight, it is necessary to exclude from the theatre all fabrics except ordinary cotton for sheeting and outer protective clothing.

The question of risk arising from garments other than the outer cotton one is often raised. A close fitting cotton outer garment which encloses all other garments will largely prevent the separation of their surfaces which could be a source of static. There would not appear to be any significant risk of static from such garments. This conclusion is also reached by Guest, Sikora and Lewis.[1]

* Measured under testing conditions defined by British Standard Specifications B.S. 2044: 1953 and B.S. 1938 (1953).

ANTISTATIC AGENTS

Various antistatic surface treatments are applied to nylon, silk, etc., to facilitate spinning and weaving. These antistatic materials, which are either hydroscopic salts or water soluble waxes based on polyethylene glycol, and reduce the resistance of the surface of fibres by a factor up to 10 000 times, are effective in conditions of low relative humidity.(5)

Unfortunately all these materials appear to be water soluble so that re-treatment is necessary each time the article is laundered.

Plastic sheeting can be treated with such materials, but in the author's opinion this material may give rise to such a high degree of risk that it should be excluded from the theatre except when used in a wet condition.

The resistance per unit square of cotton at 65% relative humidity and of antistatic treated fabrics is of the order 10^9 to 10^{11} Ω and is higher than would be desirable were lower surface resistances possible, so that the rate of separation of such fabrics in the most hazardous zone should be slow and preferably not exceed 100 cm^2/sec.

TIME TO REACH EQUILIBRIUM WITH ATMOSPHERIC HUMIDITY

As some time is required for cotton and other fabrics to attain equilibrium with the atmospheric humidity, the article should be freely exposed for a minimum of 10 min after removal from sterilizing drums, warm cupboards, etc., otherwise even cotton materials may be the source of dangerous charges.

To summarize, the conclusions of the essential factors for safety from static in operating theatres are:

1. All rubber articles in use and the floor of the rooms to be not less than 100 000 Ω and not more than 10 MΩ resistance [measured under conditions defined in British Standard (B.S. 2044 and B.S. 1938)].
2. All highly insulated surfaces such as plastic sheeting (except when wet), artificial leather, nylon, rayon, wool, silk and synthetic fibres must not be used in the theatre.
3. Close fitting cotton outer garments which completely cover other garments should be worn.
4. Such cotton garments and towels, cotton sheeting, etc., should be freely exposed to the theatre atmosphere for a minimum of 10 min before being used.
5. The relative humidity of the theatre atmosphere must be maintained at not less than 65%. A suitable humidity indicating instrument should be fitted in the theatre.
6. Antistatic surface treatment agents should be considered as a method of increasing the conductivity of fabrics without control of the atmospheric humidity being necessary. Such treatment would have to be undertaken as part of the normal laundering process.

ACKNOWLEDGEMENTS

This article is based on work carried out at the Research Centre of the Dunlop Rubber Co., Ltd., and the author expresses his thanks to the Directors for permission to publish these results.

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DISCUSSION

Mr. A. W. Pratt: The upper limit of resistance to earth of 10 MΩ is based on the consideration of the time of discharge of a condenser with a leakage path to earth and hence in parallel with the spark gap. Circumstances may arise in which the conducting medium is in series with the spark gap, as, for instance, where a person effectively connected to earth approached a patient lying on an insulated mattress and charged to a potential of several thousand volts relative to the trolley due, say, to the removal of a warm, dry blanket. F. T. Farmer (Royal Victoria Infirmary, Newcastle-upon-Tyne) has investigated this particular problem in which the conducting medium, e.g. conducting rubber tyres and trolley wheels, will be in series with the spark discharge occurring just before the patient is touched. Farmer has calculated that the energy given to the spark increases as the value of the series resistance is raised from zero and that there is a marked increase in the explosive risk as the resistance of the conducting medium is raised from 10^5 to 10^7 Ω for initial voltages of 20 kV and above. The analysis emphasizes that the resistance to earth should be as low as possible compatible with the requirement to safeguard personnel in the event of faults developing on unearthed equipment. The lower limit of 100 000 Ω quoted by Bulgin should therefore be aimed at.

Author's reply: I am not familiar with Dr. Farmer's argument on the effect of added series resistance but experimental work by Boyle and Llewellyn* on the effect of added series resistances up to 500 000 Ω (the highest values used) shows that the energy required for ignition of ether–air mixtures was only affected to a small degree. The general tendency was, however, to increase the energy required with capacities of the order expected in an operating theatre and with voltages of the order of 5 kV.

It is important in practice that all insulating items should be replaced by anti-static constructions so that the conditions envisaged in the question do not arise.

* Boyle and Llewellyn. *J. Soc. Chem. Ind.*, **66**, p. 99.

Safety measures in operating theatres and the use of a radioactive thallium source to dissipate static electricity

By A. Quinton, M.Sc., A.Inst.P., United Birmingham Hospitals, Edgbaston, Birmingham

Precautionary measures to minimize the risk of explosions due to the ignition of anaesthetic gas mixtures are described briefly. Special attention is given to the elimination of charges of static electricity, including the use of an apparatus incorporating a radiothallium source.* The apparatus causes a stream of air to pass over the radiothallium and the ionized air so produced is effective in removing electrostatic charges at distances up to 6 ft. The radiation risk to theatre personnel is negligible. Some interesting measurements concerned with the safety of the use of plastics and the wearing of nylon stockings are given.

The use of anaesthetic gas mixtures such as ether–air in operating theatres does involve an explosive risk of which we are reminded from time to time by experiencing or reading about a theatre explosion. Fortunately, all the necessary conditions for an explosion rarely occur together. Briefly, these conditions are (i) the presence of an explosive mixture above a minimum concentration, (ii) a spark of sufficient energy or a surface hot enough to cause ignition.

Measures to eliminate or reduce explosive risk may be considered under the following headings:

(*a*) If the operation includes surgical diathermy or some other procedure where the source of ignition is obviously present, then explosive anaesthetics should be avoided.

(*b*) Explosions are likely to occur in spaces where anaesthetic gas can accumulate. The concentration can be kept low in the theatre as a whole by good ventilation, preferably extracting the air at a low level and by preventing the escape of anaesthetic gas from the apparatus and patient (closed-circuit anaesthesia). It is bad practice to cover any space near the anaesthetic apparatus or patient with a sheet as a pocket of air containing a high concentration of gas may result. In this respect, careful design of sucking units is essential.

(*c*) Electrical apparatus is an obvious source of sparking and particular care has to be directed towards switches (mercury switches should be used or the switch incorporated in an earthed, gas-tight box) and to electric motors (induction type motors should be used or the ordinary type enclosed in a special earthed shield). All metal parts should be earthed and cables and fittings inspected regularly. Apparatus such as cystoscopes and oesophagoscopes, used for illumination inside the patient, should be battery operated and carefully constructed.

(*d*) Sparking may also arise from the discharge of static electricity and safety measures should be designed to prevent the accumulation of static electricity and to maintain conducting surfaces at a common potential. The remainder of this paper will be devoted to methods of achieving this without incurring the possibility of shocks from electrical apparatus.

PLASTIC SURFACES

Certain materials such as perspex, polythene, nylon, are dangerous in operating theatres because they readily acquire a potential of 1000 V or more.

MOBILE EQUIPMENT

Equipment such as trolleys, bowl stands and so on, when moved about the theatre can acquire a potential several hundred volts different from stationary equipment, and it is possible for a discharge of static electricity to take place. In the past, this problem has been partially solved by trailing earthing chains, but the method fails when the chains become dirty or break and a better method is to use wheels fitted with conducting rubber tyres. The resistance to earth of the metal parts of a trolley depends on the loading and also the effectiveness of the contact with the floor. For test purposes, the trolley is placed on a metal plate and the rubber tyre is made clean and moist to ensure a good contact. The resistance between the metal part of the trolley and the metal plate should be of the order of 100 000 Ω, when the trolley is lightly loaded.

THEATRE PERSONNEL

Theatre staff should not wear plastic aprons because of the dangerous potentials these materials easily acquire. They should also wear conducting rubber footwear so that any potentials acquired are rapidly dissipated or prevented from being produced. The conducting rubber mix is made conducting by the addition of graphite. The footwear is tested by making good contact with the inside sole with one moist metal plate, 1 × 1 in, and similar contact with the outside sole. The resistance between the foot of the wearer, standing normally, and the floor should be of the order of 100 000 Ω.

Experiments have been made to determine whether different types of stockings have a significant influence on the total resistance between the skin and the outside of the rubber sole. This resistance was measured, on a volunteer nurse, by measuring the current flowing when voltages up to 4000 V were applied between the thigh and the outside sole. The results are indicated in Table 1 and it will be noticed that

Table 1. *Through resistance for different footwear and stockings*

		Resistance (MΩ)	
Type of stocking	*Leather*	*Plimsoll of conducting rubber*	*Ankle length conducting rubber*
—	100–250	0·35–0·62	0·2–0·4
Nylon	100–150	0·30–0·60	0·2–0·7
Lisle	100–200	0·37–0·73	0·3–0·4

there is no significant difference that would justify the banning of nylon stockings. The explanation appears to be that the nylon thickness is very small and contact between the skin and the boot is maintained by the skin bulging through the nylon mesh. The nurse noticed a tingling sensation when the current was approximately 100 μA.

RELATIVE HUMIDITY

The generation of static electricity is more difficult in a damp atmosphere or if the surfaces concerned are covered with a fine film of moisture. It is good practice to damp surfaces such as rubber before use and the mopping of the theatre floor helps to reduce explosive risk. In some countries

* British Patent applied for No. 4369/53.

(Sweden), the operating theatre is kept at a high relative humidity (70–75%) to reduce the production of static charges, although this practice renders work in theatres uncongenial.

RUBBER PARTS OF ANAESTHETIC APPARATUS

Special care has to be paid to the anaesthetic apparatus because the concentration of anaesthetic gas is almost certainly above the minimum value and the apparatus is connected to the patient. Danger may arise from the flow of gas through rubber tubes, the movement of the breathing bag or from friction when the various parts are connected together. The danger is minimized by using conducting rubber (100 000 Ω/cm^3 resistivity) or by coating the rubber with a conducting wax. Experiments using a radioactive source in the anaesthetic apparatus itself are being made in an effort to reduce the explosive risk (this work being done at the suggestion of my colleague, Mr. W. H. Bond).

THE USE OF IONIZING RADIATIONS

In industry, static electricity developed on belts or fibres has been reduced by the direct action of ionizing radiations from suitable radioactive sources. This is not possible in operating theatres since it might result in the repeated subjection of the theatre staff to small doses of radiation greater than the maximum permissible dose (0·5 r/week). Similarly, streams of ionized air produced by sparking or ultra-violet radiation are not possible in theatres due to the obvious danger caused by sparks.

Figs. 1 and 2 indicate how a radioactive thallium source can be used safely in the production of a stream of ionized air.

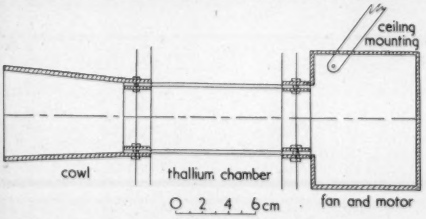

Fig. 1. Diagram of radioactive thallium ion blower

A small induction motor blows a stream of air down a brass cylinder having length 10 cm, diameter 5 cm, and thickness 2 mm. The cylinder is lined on its inside curved surface with a metal foil incorporating radiothallium^{204} at a strength of $\frac{1}{4}$ mc/cm^2, making 50 mc altogether. The radiations from the thallium ionize the air, but very little radiation can escape into the theatre. The ionized air is carried into the theatre and acts as a high resistance preventing or dissipating static electricity and reducing explosive risk. The stream of ionized air should be directed at the space where static charges are likely to develop and where they may be highly dangerous.

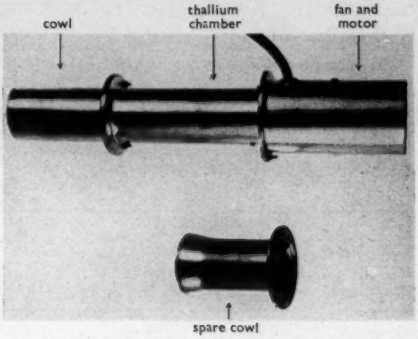

Fig. 2. Photograph of radioactive thallium ion blower

Such a space is the region near the patient's head and the anaesthetic apparatus. It is not suggested that this "ion blower" removes risk and can replace the other precautions described, but it does represent a useful additional precaution. Table 2 shows the results obtained with the ion blower when it is directed at a charged brass surface situated about 6 ft away. The voltage on the charged plate was measured by an electroscope and also by a stati-gun devised by Bulgin. The flow of air was just perceptible at this distance and was not unpleasant.

Table 2. *Dissipation of static charge by the ion blower at various distances*

Distance (ft)	*Source*	*Voltage (kV) Initial*	*Final*	*Time (sec)*	*Effective resistance (Ω)*
5	15 mc Tl^{204}	2·66	2·04	5	$9{\cdot}5 \times 10^{11}$
6	15 mc Tl^{204}	2·66	2·04	5·8	$11{\cdot}1 \times 10^{11}$
7·5	15 mc Tl^{204}	2·66	2·04	8	$15{\cdot}2 \times 10^{11}$

These results were obtained with the first model using an axial single side thallium source and the new model shown in Fig. 1 should give better results.

Stray radiation. Measurements of the radiation on the axis of the apparatus gave the following readings:

Distance from end (in)	6	12	18
Radiation (mr/h)	4	1·3	0·3

The radiation is well within safe limits and at the working distance of 5–6 ft is very small indeed.

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DISCUSSION

Mr. A. W. Pratt: In introducing his paper Mr. Quinton stated that in his own experience the relative humidity of the theatre averages about 50–55% though other measures to minimize the risk of explosion due to static electrification are observed. To what extent can humidity be disregarded or used as a remedial measure to be specially applied, particularly as two other authors at this conference recommend that the relative humidity should not be allowed to fall below 65% (Bulgin) or 70% (Forrest)? We may note that Silsbee* states that if the relative humidity can be raised to 75% static

* SILSBEE (Civc. C438 National Bureau of Standards).

effects are practically certain to disappear. The objection has been raised that a humidified atmosphere would tend to produce uncongenial working conditions in an operating theatre, but I cannot believe that 65%, or even 70%, would produce any marked unpleasantness. Medical opinion should be sought on whether there is a valid reason why surgical operations should not be carried out at these higher humidities. To what extent is controlled humidification used in the air conditioning of theatres and do the statistics of theatre explosions due to static electrification afford any evidence of the value of humidification? I think this can be important because conditioned air, unless it is humidified, will tend to enhance the risk of explosion in cold weather.

Finally, the description of the tests for the resistance of the conducting media do not include the resistance of the floor. No doubt this is implied, but in view of the fundamental importance of the floor resistance it should be specifically stated.

Dr. A. Bracken: Humidity as a means of safeguarding against static electrification is unreliable because (*a*) discomfort at 70% R.H. may lead to its being unpopular and (*b*) the apparatus is often warmer than the room, so that no moisture film collects. This especially applies to the rubber articles which are warmed by the patient's breath (mask, hose and bag) and which are in the vital area. It is interesting to find that static electricity is a nuisance in moist counties such as Lancashire. Chains are of very little use, it is far better to use a weighted braided cable, for earthing trolleys.

Ultimately the solution must be a completely non-inflammable new anaesthetic. Perhaps the fully fluorinated hydrocarbons will supply the need.

Mr. D. Bulgin: Commenting on Dr. Bracken's remarks, humidity is only of value in relation to reducing the resistivity of fabrics. We have recently devised a fabric of an appropriate resistivity independent of the relative humidity by using a proportion of fibres containing carbon black (subject to provisional patent).

Author's reply: Replying to Mr. Pratt; in my experience, the humidity of theatres where there is no special control varies from 30 to 55% according to the season and it is undoubtedly true that static electricity is easily demonstrated at humidities lower than 55%. When the humidity is 65% or over, a film of moisture seems to form on solid objects and the demonstration of static charges is very difficult. My own opinion is that operating theatres where the humidity is higher than 65% and the temperature is of the order of 72° F are not conducive to hard work. Undoubtedly, theatre personnel could get used to these working conditions, but I advocate that the relative humidity should not be allowed to fall below 50% and that other measures be taken, such as the use of an ion blower to minimize the danger from static electricity. This would have the advantage of avoiding complicated and expensive humidification apparatus and also making the working conditions in the theatre more congenial. I agree with Mr. Pratt's comments that the resistance of the floor should be kept at a suitable low value (1 to 10 MΩ) and the provision of such a floor is the first and most important step in minimizing static electricity risk.

I agree with Dr. Bracken's comments and would like to stress his point that the provision of a controlled humidity of approximately 70% would not completely ensure freedom from risk. It is agreed now that earthing chains are of little value; castor wheels with conducting rubber tyres are very much better.

Special note: Since the conference, experiments have shown that the stream of ionized air produced by the ion blower need not be directed at the objects whose surfaces have become electrically charged. The ionized air, if produced at a reasonable distance from such surfaces, is attracted to them and causes them to be discharged. These experimental facts greatly enhance the performance of the ionized air blower.

The electrostatic ignitibility and electrification of finely powdered Hexamine

By A. G. Peace, B.Sc., Ph.D., A.Inst.P., Physics Department, North Staffordshire Technical College, Stoke-on-Trent

It is shown that finely divided dry Hexamine powder when dispersed in a dust cloud can be ignited by electric sparks of energy less than 0·005 j and that certain previously established principles of spark ignition apply also to this substance. No ignition of heaped powder by similar means could be produced. The powder is shown to be readily electrified in various mechanical operations similar to those used in manufacturing processes, charges of the order of 10^{-9} C/g being produced.

Since the publication of *Fire and explosion risks*[1] in 1904 it has been increasingly recognized that under suitable circumstances clouds of dust of many substances, not all regarded as dangerously inflammable in bulk, may be caused to burn, with explosive effect if confined. In industrial processes the danger to life and property resulting from such explosions is considerable and much work has been done in attempting to ascertain the conditions necessary for an explosion to occur.

One of the possible causes of dust explosions which has been studied intensively in recent years is the discharge of static electricity accumulated in industrial processes. While the investigations have not yet resulted in a comprehensive theory of spark ignition, the following important principles, some of which are of considerable practical importance, have been established:—

(i) For every substance there is a minimum dust concentration below which no spark, whatever its energy or character, will cause ignition. This minimum is very difficult to determine precisely, but it can usually be found with sufficient accuracy for practical purposes.

(ii) For every substance a minimum energy is required for ignition. This is probably true of the actual energy dissipated in the spark gap itself, but since the measurement of this latter quantity is difficult, the statement refers to the total electrostatic energy stored in a suitable charged body, e.g. a condenser in a laboratory experiment or a piece of machinery in a works, used to produce the spark; although a proportion of this energy will be radiated as electromagnetic waves, and some dissipated resistively, the energy of the charged body is obviously of most interest in assessing the industrial hazard.

(iii) In order to obtain ignition with minimum energy the discharge must take place through a resistance, the optimum

value of which increases as the capacity of the object being discharged decreases. The resistance is between 10^4 and $10^6\ \Omega$ for capacities of the order likely to be encountered in practice. The rate of variation of ignition energy with resistance on either side of the minimum differs considerably between one substance and another. Observations on the discharge by means of a cathode-ray oscillograph show[2] that the optimum resistance is approximately that at which the discharge changes from high-frequency oscillations to a predominantly unidirectional spark, suggesting that the time distribution of energy in the discharge is of paramount importance.

(iv) The minimum ignition energy decreases with diminishing particle size in the cloud.

(v) There appears to be no correlation between the ignitibility of a dust cloud and that of a heap of dust of the same substance.

In this paper an account is given of a typical investigation into the possibility of the ignition of dust by the discharge of static electricity accumulated in an industrial process. An investigation of this kind to be complete must consist of two parts: firstly, a study of the ignitibility of the substance in bulk and also dispersed in a dust cloud, and, secondly, a determination of the amount of static electricity likely to be generated and accumulated in the industrial process. With regard to the second part, the industrial conditions are often not suitable for the conduct of controlled experiments on a full scale, but it is frequently possible as in this case to simulate the working conditions in the laboratory; although when this is done there may be some degree of uncertainty in scaling up the results to plant conditions, it is usually possible to obtain a sufficiently accurate estimate of the hazards involved to give useful guidance to those concerned with the construction and operation of the plant.

IGNITION OF HEXAMINE BY ELECTROSTATIC SPARKS

(*a*) *Dust clouds.*

Fig. 1 shows the apparatus, consisting of a glass bulb, in which a dust cloud could be raised by means of an air blast

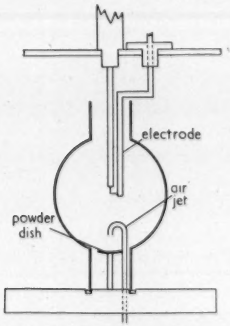

Fig. 1. The explosion bomb

and ignited by sparks between the central electrodes at a predetermined time after the application of the air blast.

This apparatus was used to determine:—

(i) The minimum energies (measured on charged condensers of various capacities) required for spark ignition of Hexamine dust clouds of ample concentration; (ii) the minimum dust concentration which could be ignited by sparks of energy well in excess of the minimum.

(i) *Minimum ignition energy.* In view of the general conclusions drawn from previous experimental work on other substances referred to above, this series of experiments resolved itself into a determination of minimum ignition energies over a range of resistance values for each capacity. The absolute minimum energy and the corresponding series resistance for each capacity could then be picked out.

The circuit used is shown in Fig. 2; a large capacity condenser could be charged from the diode output and then used

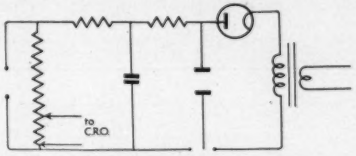

Fig. 2. Circuit for spark production and voltage measurement

as a reservoir from which the small discharge condenser could be charged at will, and unidirectional sparks obtained. The voltage across the discharge condenser just before a spark passed was measured by means of a cathode-ray oscillograph which had been previously calibrated by means of a d.c. potential; it is estimated that the values as read were accurate to within about 5% so that the resultant condenser energies, allowing for a variation of $\pm$ 10% from the nominal values of the condenser capacities, should be accurate to about $\pm$ 20%.

In the table the results of this series of experiments are shown, two limiting energy values being given in each instance. The higher of each pair of energies is the minimum value at which ignition could be obtained once in ten trials, whilst the lower of each pair is the maximum energy of discharges which did not give a single ignition in ten attempts. As it was not possible to vary the sparking voltages continuously with the apparatus available, the recorded energy bracket is possibly wider than it need be in some cases, and the true minimum ignition energies probably lie not far below the maxima and certainly well above the minima recorded in the table.

Minimum ignition energies in joules for Hexamine dust clouds of approximate concentration 400 *mg/l*

Condenser capacity, μF / *Resistance, kΩ*	0·001	0·00055	0·0002
0	0·013–0·018	0·0097–0·012	more than 0·0023
15	0·008–0·01	0·0075–0·0097	more than 0·0023
50	0·004–0·0048	0·005–0·0062	more than 0·0023
68	0·004–0·0048	0·004–0·0048	0·0013–0·0018
82	0·004–0·0048	0·0031–0·004	0·0013–0·0018
100	0·004–0·0048	0·004–0·0048	0·0018–0·0023
1000	0·0064–0·01	0·0056–0·0069	more than 0·0023

The above experiments were carried out with dry powder which passed 150 B.S.S. sieve and had subsequently been dried in a steam oven for at least one hour to ensure good dispersion in the cloud. No increase in sensitivity was discovered when powder at a temperature of 110–120° C was used instead of 80° C, the normal powder temperature for the experiments.

The difficulty of obtaining a uniform dispersion increases considerably with the size of the dust particles and time has not permitted a full investigation to be made of minimum ignition energies for coarse powder. However, trials were made with "Hexamine fine powder" supplied by Messrs. Brotherton & Co. Ltd. (Wakefield); a sample of this analysed as follows:—

Sieve mesh	20	30	60	80	120	150	through 150 B.S.S.
% left on	6·4	3·16	13·0	33·2	33·6	9·3	1·34

With this powder (after drying as before) no ignitions were obtained under the following conditions:—

Dust concentration approximately 400 mg per litre.
0·001 μF condenser energy 0·024 j; resistance 50 000 Ω.
0·0002 μF condenser energy 0·0023 j; resistance 50 000 Ω.

It is interesting to note that in 400 mg of this powder only about 5 mg would pass through 150 mesh sieve and only about 40 mg through 120 mesh; there would thus be little chance of an ignitible concentration of this fine material in the neighbourhood of the spark gap (see below).

(ii) *Lower explosion limit.* Because of the difficulty of ensuring uniformity of the dispersion a very large number of experiments would be necessary to obtain results of high accuracy. However, using adequate energy (0·001 μF charged to 5 kV, 0·0125 j) it was found possible to explode a quantity (passing 150 B.S.S. mesh) which, allowing for a small proportion which remained in the dish, was rather less than 30 mg per litre. This figure can be compared with the figure of 15 to 35 mg per litre obtained for induction coil ignition in the Safety in Mines Research Buxton gallery using 200 mesh powder.[3]

No ignitions were obtained with smaller quantities of powder, but because of the extremely small quantity used, the dispersion was very irregular and it was difficult to gauge the instant of optimum dispersion for passage of the spark; the true minimum concentration may therefore be much less than 30 mg per litre.

(*b*) *Heaped powder.*

For this series of experiments Hexamine powder was packed around a fixed electrode (1/16 in ball), the other electrode was located vertically above, the gap being adjustable. This apparatus was substituted for the explosion bomb in the circuit of Fig. 2. No matter what series resistance was used it was found impossible to ignite the Hexamine with sparks from a 0·001 μF condenser charged to 7 kV. A spark of energy 0·2 j passing from a 0·01 μF condenser caused a transient flame which disappeared as the spark ceased, to appear on top of the material; this effect was practically independent of the series resistance. Sparks of greater energies merely dispersed the material or, if this was confined by a little damp filter paper, caused similar temporary flaming.

In no case could true ignition be produced, so it is evident that the danger of ignition of Hexamine in bulk by electrostatic sparks is negligible, and the matter was not pursued further.

ELECTRIFICATION OF HEXAMINE POWDER

In the industrial processes for the production of Hexamine the powder is dried by being constantly upset from rotating vanes in a stream of dry warm air. Similar processes are known to produce considerable quantities of electricity and it was thought advisable to discover whether the same was true in this case.

The experiments were simply contrived to give a means of measuring the voltage produced on a model of the industrial drying machine containing "Hexamine fine powder" dried as before. A Lindemann electrometer was used to measure the potentials produced and the capacities of the various plates, etc., were determined by repeated sharing of their charge with a standard 0·1 μF condenser.

The remarkable influence of atmospheric conditions on static phenomena was incidentally demonstrated by the fact that several days elapsed before consistent readings could be taken owing to the smallness of the voltages produced and the relatively low leakage resistances between various parts of the apparatus (10^9 Ω). A certain day of good convection, thus giving low humidity in the lower layers of the atmosphere, enabled satisfactory readings to be taken, leakage resistances then rising to more than 5×10^{10} Ω during the day. Charges of the order of 10^{-9} coulomb/g were measured on the Hexamine leaving the model drier.

In order to examine the effects of separating the powder from surfaces of different materials, Hexamine was upset from plates of similar size of clean brass, clean Duralumin, rusty steel, Duralumin coated with a layer of Hexamine and rusty

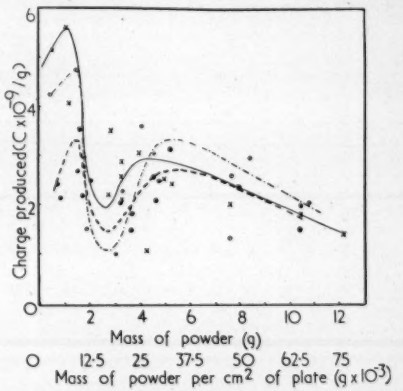

Fig. 3. Electrification of Hexamine by upsetting powder from various plates

Plate	Observed values	Suggested trend of variation
Duralumin coated with damp Hexamine	×	———
Clean Duralumin	○	— — — — — —
Rusty steel coated with damp Hexamine	●	— — — — — —

steel coated with Hexamine. The results for all the surfaces were of the same order of magnitude, three typical cases being shown graphically in Fig. 3.

The shape of the curves in Fig. 3 can be accounted for most satisfactorily in terms of the ratio

$$\frac{\text{quantity of powder in contact with the plate}}{\text{total quantity of powder on the plate}}$$

taking account of the effect of increased pressure on closeness of contact. The first peak corresponds to a situation where the powder present is just sufficient to coat the plate all over

(about 0·01 g/cm^2 with the grade of powder used) and the second where the above ratio is not yet sufficiently small to outweigh the increase in charge produced by the greater closeness of contact with the plate. The trough between indicates that until the powder exceeds around 0·02 g/cm^2 this increased closeness of contact is not sufficient to enhance charge production to any great extent. Subsequently the graph presumably goes asymptotically to zero since a certain maximum charge per unit area of plate cannot be exceeded no matter how much powder is piled on top. The dry powder was also sieved through both 60 mesh and 20 mesh copper sieves. The charge generated in this process was reasonably consistent, around $0{\cdot}5 \times 10^{-9}$ C/g.

Further experiments showed that undried Hexamine became electrified in similar processes at a rate not exceeding 1/100 and probably nearer 1/1000 that of the dry product. (Hexamine is hygroscopic and the powder used here was taken from a partly filled tin which had been left open to the air for some days.)

SUMMARY AND CONCLUSIONS

1. Previous experimental work has led to the establishment of certain general conclusions regarding the ignition of dry dusts by non-inductive sparks. It has been shown that dry Hexamine powder can fall into the category of substances to which these conclusions apply.

2. If the powder is finely divided (passing 150 mesh) and dispersed in a dust cloud, the energy required for spark ignition is less than 0·005 j.

3. As the particle size increases the amount of energy required for ignition also increases considerably.

4. Heaped powder (as distinct from an air dispersion) can apparently not be ignited by sparks of energies likely to be encountered in practice.

5. Experiments have shown that electrostatic charges of the order of 10^{-9} C/g can be produced in various mechanical operations similar to those used in manufacturing processes.

To determine whether this electrification could give rise to a dangerous spark in a particular plant it would be necessary to have information about the rate of flow of the Hexamine, the size of the machinery, the efficiency of earthing, etc.; calculations for a plant of average dimensions suggest that in unfavourable circumstances (dry weather, faulty earthing) charges might accumulate sufficiently to give rise to sparks capable of igniting a cloud of dry Hexamine powder.

ACKNOWLEDGEMENTS

This work was done in the Department of Inorganic and Physical Chemistry of the University of Leeds and I am indebted to Professor E. G. Cox for suggesting the problem and providing facilities. I wish to thank Messrs. Brotherton & Co. Ltd. for the gift of a quantity of Hexamine and for giving me facilities for examining their Hexamine plant.

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DISCUSSION

Dr. E. C. Craven: Whilst it is true that Hexamine in a solid form is not readily ignitible, the two most used forms of portable pelleted fuel are metaldehyde and Hexamine. In tablet form these are almost invariably ignited by a match.

Author's reply: I am not acquainted with the exact composition of tablets of portable fuel, but Dr. Craven's remark seems to indicate that the Hexamine variety must contain some form of initiator or possibly a drying agent. No samples of commercially available Hexamine would ignite readily with even a bunsen flame. In addition, the amount of water collected by the crystals in a moist atmosphere precludes easy ignition.

The ignition of explosives by condenser discharges—effect of added circuit resistance

By G. MORRIS, Ph.D., F.Inst.P., Imperial Chemical Industries Ltd., Stevenston, Ayrshire

To investigate the mechanism of ignition of explosives by capacitance sparks, the critical ignition energy of lead trinitroresorcinate has been examined for a wide range of capacitance and series resistance.

The experimental data do not completely conform to the same energy/time relation as for ignition by hot wires. A useful empirical relation is, however, found. The use of added resistance in earth lines is shown to decrease plant safety.

The explosives industry is one of those in which the presence of uncontrolled static charges may lead to a major accident. The explosives which are manufactured commercially fall, with respect to their sensitivity to ignition by capacitance sparks, into two main classes, the initiators which require from 10^{-6} to 10^{-2} joules, and secondary explosives which require spark energies of the order of 10 joules to cause ignition even when confined.(1)

To simulate plant conditions, explosives are usually tested in the form of small heaps of powder through which the spark is made to pass. The reaction to sparks, therefore, may not be the same as for the more widely studied mixtures of gases and solvent vapours, and air-borne dusts.

It was known(1) that for small condensers the energy necessary to fire initiating explosives such as lead trinitroresorcinate was independent of the capacitance of the test

apparatus, but that as the size of the condenser was increased the critical energy suddenly increased rapidly, and there was evidence of a critical voltage below which ignition with a particular arrangement of electrodes was not possible. A similar behaviour has been observed by Boyle and Llewellyn[2] with solvent vapour/air mixtures.

In testing the secondary explosives which have very large critical energies of ignition large capacitances have to be employed if the charging voltages are to be kept to reasonable values; the effect of these large condensers on the observed ignition energies requires investigation. It was also desired to investigate the effect of adding resistance to the discharge circuit, both as a possible safety device and with a view to investigating the spark mechanism of ignition.

Boyle and Llewellyn have shown for dusts[3] and vapours[2] that the introduction of a resistance of the order of $10^5\ \Omega$ into a condenser discharge circuit causes a reduction in the amount of electrical energy which has to be supplied for ignition. It is believed that the mechanism involved here is that the resistance prevents oscillatory discharge which is known to be less incendive than a direct discharge. With larger resistances, however, the addition of resistance to a condenser discharge circuit will increase the total energy which has to be supplied for ignition. Two mechanisms are effective here: (i) it will increase the time of duration of the discharge and so add to the energy wasted by heat losses; (ii) some heat will be dissipated in the resistance instead of at the spark gap.

The present paper describes tests which have been made to measure these effects for lead trinitroresorcinate which is known to be very sensitive to condenser spark ignition. The apparatus used has been described elsewhere[1] and the test consisted of placing a pile of a few milligrams of the explosive on a steel plate and bringing a gramophone needle nearer to the plate through the heap until discharge occurred.

Previous workers on spark ignition have adopted different criteria of ignition. In these tests the procedure was to make a fixed number of trials, usually 50, at each of a range of voltages and to report the percentage ignitions obtained. The value quoted is that giving 50% ignitions. The standard deviation of the experimental tests should also be quoted as this enables the probability of ignitions at other energy levels to be assessed. It should be noted that the standard deviation is most simply obtained graphically from the slope of the distribution plotted on probability paper.[4] In the application of laboratory measurements to plant conditions it is frequently required to know the energy corresponding to probabilities of ignition of the order of one in a million. It cannot be safely assumed that the energy distribution is normal to a sufficient accuracy to permit this to be calculated. A useful empirical rule which has been employed in the explosives industry is to take 1/20 of the 50% ignition value and use this as a safe level in, for example, estimating the maximum resistance to earth of movable charged conductors such as operatives.[1] This value corresponds to a risk of ignition of once per million trials, if the distribution were accurately normal with a reduced standard deviation of 0·2. The experimental 50% ignition values for a wide range of capacitance and of resistance added to the discharge circuit are shown in Table 1, from which it will be seen that as both capacitance and resistance increase the ignition level rises markedly.

For the large condensers it was found that direct discharge with no added resistance caused so violent a spark that the lead trinitroresorcinate, if not ignited, was blown away from the path of the spark. Since this was taken as an alteration

Table 1. *Effect of circuit resistance on the spark ignition of lead trinitroresorcinate*

[σ = standard deviation of results]

Capacitance (μF)	*Resistance* (MΩ)	50% *volts* V_{50}	50% *energy (joules)* E_{50}	σ/E_{50}
0·0005	0	610	$9{\cdot}3 \times 10^{-5}$	0·16
	0·01	700	$1{\cdot}21 \times 10^{-4}$	0·09
0·001	0	550	$1{\cdot}51 \times 10^{-4}$	0·11
	0·01	620	$1{\cdot}92 \times 10^{-4}$	0·15
	0·10	830	$3{\cdot}45 \times 10^{-4}$	0·05
	0·50	880	$3{\cdot}88 \times 10^{-4}$	0·05
	1·0	920	$4{\cdot}24 \times 10^{-4}$	0·09
0·002	0	470	$2{\cdot}2 \times 10^{-4}$	0·22
	0·01	510	$2{\cdot}6 \times 10^{-4}$	0·13
	0·10	770	$5{\cdot}93 \times 10^{-4}$	0·05
	0·50	800	$6{\cdot}40 \times 10^{-4}$	0·14
	1·0	840	$7{\cdot}05 \times 10^{-4}$	0·09
0·006	0	330	$3{\cdot}47 \times 10^{-4}$	0·18
	0·01	450	$6{\cdot}10 \times 10^{-4}$	0·11
	0·10	700	0·00147	0·14
	0·50	720	0·00156	0·14
	1·0	740	0·00164	0·09
0·01	0	330	$6{\cdot}48 \times 10^{-4}$	0·16
	0·01	400	$8{\cdot}00 \times 10^{-4}$	0·21
	0·10	640	0·0021	0·12
	0·50	680	0·0023	0·19
	1·0	700	0·0025	0·09
0·02	0	250	$6{\cdot}25 \times 10^{-4}$	0·10
	0·01	380	0·00145	0·30
	0·10	600	0·0036	0·10
	0·50	640	0·0041	0·09
	1·0	700	0·0049	0·11
0·05	0·01	360	0·00324	0·26
	0·10	580	0·00842	0·13
	0·50	600	0·0090	0·07
	1·0	680	0·012	0·09
0·1	0·01	340	0·0058	0·20
	0·10	550	0·015	0·13
	0·50	600	0·018	0·13
	1·0	650	0·021	0·09
0·5	0·01	330	0·027	0·32
	0·10	470	0·053	0·08
	0·50	570	0·081	0·16
	1·0	630	0·099	0·10
	10	1500	0·56	0·16
	35	2600	1·70	0·28
	100	4600	5·24	0·19
1·0	0·01	310	0·048	0·28
	0·10	440	0·097	0·15
	0·50	560	0·157	0·18
	1·0	600	0·180	0·12
	10	1200	0·72	0·18
	35	1500	1·10	0·5
	100	3900	7·6	0·08

Table 1.—*continued.*

Capacitance (μF)	*Resistance* ($M\Omega$)	50% *volts* V_{50}	50% *energy (joules)* E_{50}	σ/E_{50}
2·0	0·01	300	0·090	0·34
	0·10	420	0·177	0·08
	0·50	560	0·314	0·13
	1·0	605	0·365	0·08
	10	880	0·77	0·10
	35	1200	1·40	—
	100	3500	12·3	0·10
4·0	0·01	220	0·096	0·31
	0·10	410	0·337	0·21
	0·50	560	0·629	0·14
	1·0	600	0·720	0·09
	10	750	1·12	0·18
	35	1000	2·0	—
	100	2400	11·5	0·16

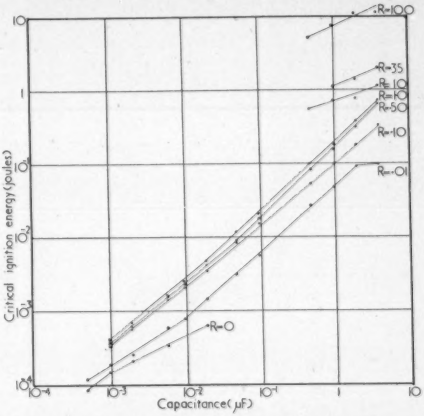
in the condition of experiment, tests are not reported for such condensers with less than 0·01 MΩ in circuit. It was also noted that when large condensers are fired in circuits of high time constant the discharge does not pass continuously but takes the form of a series of bursts of sparking. This phenomenon has been dealt with, for example, by Kip[5] and Trichel.[6]

It has been shown[7] that the energy required to ignite an initiating explosive using a hot metal filament is quantitatively the same whether the heat is supplied by a direct current or a condenser discharge of equivalent duration. For commercial fuseheads the energy, E, necessary to cause ignition, and the time, t, for which that energy is supplied can be written:

$$E = E_0 + kt \text{ with } k \text{ a constant}$$

For a condenser discharge t can be replaced by $2{\cdot}3RC$, the time during which 99% of the energy of a capacitance is dissipated, but when energy is plotted against capacitance at constant resistance, the graph obtained is not a straight line. In a log log plot as shown in the figure, E is proportional to C over the middle range of capacitance and resistance; it may be concluded (*a*) that the discharge mechanism is not the same throughout the range of condensers tested, and (*b*) that E_0 is small and the experimental data are not suitable for its accurate determination.

Table 2 shows, however, that a useful empirical result can be deduced from the experimental data. To a degree of approximation sufficient for safety precautions, the relative critical ignition energy for any added resistance is the same for all the condensers tested.



Variation of critical ignition energy for lead trinitroresorcinate with capacitance and resistance (R measured in MΩ)

Table 2(*a*). *Energy in joules needed to fire lead trinitroresorcinate* (50% *value*) *with R* MΩ *in circuit relative to that with no added resistance*

C (μF) / *R* (MΩ)	0·0005	0·001	0·002	0·006	0·010	0·020	Mean
0	1·00	1·00	1·00	1·00	1·00	1·00	1·00
0·01	1·30	1·27	1·18	1·76	1·23	2·31	1·61
0·10	—	2·28	2·70	4·24	3·25	5·76	3·65
0·50	—	2·57	2·90	4·50	3·55	6·55	4·01
1·00	—	2·80	3·20	4·73	3·86	7·82	4·48

Although it is usual directly to earth the metal frames of machinery and the like when a conducting path to earth is provided for workmen by the use of conducting flooring or the like, it is considered desirable not to have too small a resistance in the flooring as this confers protection against electrical leaks from the power mains. It has been shown[1] that quite large resistances between a conducting body and earth are sufficient to allow accumulated static charges to be dissipated safely. For example, for a man having a capacitance of 300 pF to earth, who will handle lead trinitroresorcinate and therefore cannot safely carry a charge, the electrical energy of which exceeds, say, 50 ergs, the maximum permissible earthing resistance is 10^9 Ω, even though the rate of charging is taken at the highest level reported (10^{-7} A).

It might be thought that these high resistances would so greatly increase the critical ignition energy as to make a

Table 2(*b*). *Energy in joules needed to fire lead trinitroresorcinate* (50% *value*) *with resistance R in circuit relative to that with* 0·01 MΩ *in circuit*

C (μF) / *R* (MΩ)	0·001	0·002	0·006	0·01	0·02	0·05	0·10	0·50	1·0	2·0	4·0	*Mean*	*Calculated to zero resistance*
0·01	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·00	1·41
0·10	1·80	2·28	2·41	2·62	2·48	2·60	2·59	1·96	2·02	1·97	3·50	2·38	3·37
0·50	2·02	2·46	2·56	2·88	2·83	2·77	3·11	3·00	3·27	3·49	6·55	3·17	4·46
1·0	2·21	2·71	2·69	3·12	3·38	3·72	3·63	3·67	3·77	4·06	7·50	3·68	5·19
10	—	—	—	—	—	—	—	20·7	15·0	8·6	11·8	14·0	19·7
35	—	—	—	—	—	—	—	63	23	16	21	31	43
100	—	—	—	—	—	—	—	194	158	136	120	152	214

substantial contribution to plant safety, but such a procedure would confer no significant increase in safety since, although the presence of resistance in the earth lines would affect the direct discharge to earth, it will not affect the incentivity of sparks which might pass between conductors, for example, a man and the metal frame of a machine.

ACKNOWLEDGEMENT

The author would like to thank Mr. J. King who made the greater part of the experimental tests from which Table 1 was drawn up.

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